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TENSILE TESTS FOR VARIOUS SPECIMEN CONFIGURATIONS FOR METAL MATRIX COMPOSITE P55 GR/AL 6061-T6

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FOR NAVAL SURFACE WARFARE CENTER
RESEARCH AND TECHNOLOGY DEPARTMENT

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Metallographic analysis of P55 gr/Al metal matrix composites: The fiber content was thus determined to be 40 percent, and the density of the fibers was 1.96 grams/cc. An analysis was made to determine the effect of bent specimens upon the measured elastic modulus. Tensile tests were made on dog-boned shaped specimens that conform to ASTM Standard D3552-77 and also straight-sided specimens. Results were virtually the same. Thus, straight-sided specimens could be used due to their simplicity in manufacture. Tapered soft aluminum tabs with the same width as the specimen should be used to minimize stress increase at the tabs.

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FOREWORD

The Advanced Materials Laboratory, Inc., under contract N60921-88-C-0063, performed a variety of tests on a P55 gr/Al 6061T-6 metal matrix composite panel supplied by the Naval Surface Warfare Center. These tests established the specimen shape, configuration, and other testing methods to be used for future tests in this program.

The above work was sponsored by the Small Business Innovation Research Program.

Approved by:

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SECTION 1

INTRODUCTION

A variety of tests were performed on a P55 gr/Al 6061T-6 metal matrix composite panel # G5123 supplied by the Naval Surface Warfare Center. These tests established the specimen shape and configuration and other testing methods to be used for future tests in this program. The types of tests performed were:

1. Volume fraction of the graphite fibers in the metal matrix.

2. Density of graphite fiber determination.

3. Effect of a bent specimen upon the elastic modulus.

4. Tab shape and size for optimal tensile testing results.

5. Specimen shape for optimal tensile testing results.

SECTION 2

DISCUSSION

VOLUME FRACTION AND DENSITY OF GRAPHITE FIBERS

The volume fraction of graphite fibers was determined by analyzing micrographs of the cross section of P55 gr/Al MMC. Results showed a 40 percent volume fraction of graphite in an aluminum matrix. By weighing and measuring a prismatic bar of the MMC, the graphite density was determined to be 1.96 grams/cc. These results agree with values given by John Foltz, Reference 1. For graphite single crystals, the density is 2.25 grams/cc.

MODULUS OF ELASTICITY

The modulus of elasticity for the P55 gr/Al MMC was calculated to be 22 million psi at half the ultimate tensile strength of the composite. This is due to the fact that the aluminum deforms plastically and thus has a negligible contribution to the elastic modulus of the MMC. Experimental results were close to that value. Bent specimens will lower the measured elastic modulus due to the contribution of straightening out the test specimen during a tensile test. The effect of bent specimens is shown in Figure 3.

TENSILE TESTS

Specimens were tested that had dog-boned configurations and straight sides. Also, the tapered aluminum tabs had either the same width as the specimen at the point of attachment, or a larger width than the specimen. The dog-boned specimens with a 1-inch radius of curvature, according to ASTM Standard D3552-77, Reference 2, had the highest average ultimate tensile strength of 82.3 ksi. Here, the stress concentration increased the stress by 5 percent over the nominal stress at the point of tangency between the 1-inch radius of curvature and the straight sides of the specimen. Fracture initiated at that point with a crack which then propagated parallel to the fibers to the tabs, and then continued roughly parallel to the tabs. Despite the method of crack propagation, the ultimate tensile strength is determined at the point of crack initiation. Thus, the actual ultimate tensile strength of the MMC was about 86.4 ksi. The modulus of elasticity was averaged about 18.2 million psi. which is somewhat below the 22 million psi that was calculated theoretically. This is probably due to the fact that the specimens were made from sheet material that had been bent during shearing with a paper cutter at the Naval Surface Warfare Center.

Straight-sided specimens with flush tabs were also tested. Here the tab width was the same as the specimen. The ultimate tensile strength was 82 ksi, which was practically the same as that of the dog-boned specimens. The modulus of elasticity was 21.7 million psi which is very close to that calculated theoretically.

Straight-sided specimens with tabs having a greater width than that of the specimens were also tested. The tensile strength averaged 72.3 ksi which is a reduction of that of the flush tabs. This is probably due to the stress concentrations created by the edge of the tab extending on either side of the specimen.

Dog-boned specimens with a radius of curvature of 1/4 inches were also tested. Here, again, the average tensile strength was 72.6 ksi which is below that of the 1-inch radius of curvature. Here, the stress concentration was calculated to give stresses 12 percent above the nominal stress.

Because of these results and the greater simplicity of manufacture of straight sided specimens versus dog-boned 1-inch radius of curvature specimens, future tensile tests will be performed using straight sided specimens with flush tabs.

SECTION 3

TESTS

VOLUME FRACTION OF GRAPHITE FIBERS

The volume fraction of graphite fibers were determined by obtaining a cross section of the metal matrix composite. Since this composite had continuous filaments of graphite, a cross section could be used to determine the volume fraction. The average diameter of the fibers were measured, see Figure 1. This average value was 9.61 microns (micrometers) resulting from 10 measurements. There were 67 fibers in the micrograph for a total area viewed of 10150 square microns. The region viewed was identified as the composite region. From Figure 2, one can see that the composite region is in the center of the metal matrix composite, bounded on the outside by aluminum containing no fibers. This region is identified as the aluminum region. The area of the aluminum region was 0.421 square millimeter in Figure 2 as determined by the use of a planimeter. The total area of the metal matrix composite (MMC) is 2.574 square millimeters. By using Equations (1) and (2) below, the volume fraction of graphite fibers was found.

Let: A(gr) = cross-sectional area of fibers in Figure 1

A(com) = total area of composite in Figure 1

A(Al) = aluminum region in Figure 2

A(tot) = total area of MMC in Figure 2

d = average diameter of graphite fiber, Figure 1

N = number of graphite fibers in Figure 1

f(gr) = volume fraction of graphite in the MMC

$$A(gr) = 3.14159 \times d \times d \times N / 4 \quad (1)$$

$$f(gr) = \frac{A(gr) \times [\, A(tot) - A(Al)\,]}{A(com) \times A(tot)} \quad (2)$$

f(gr) = 40 percent

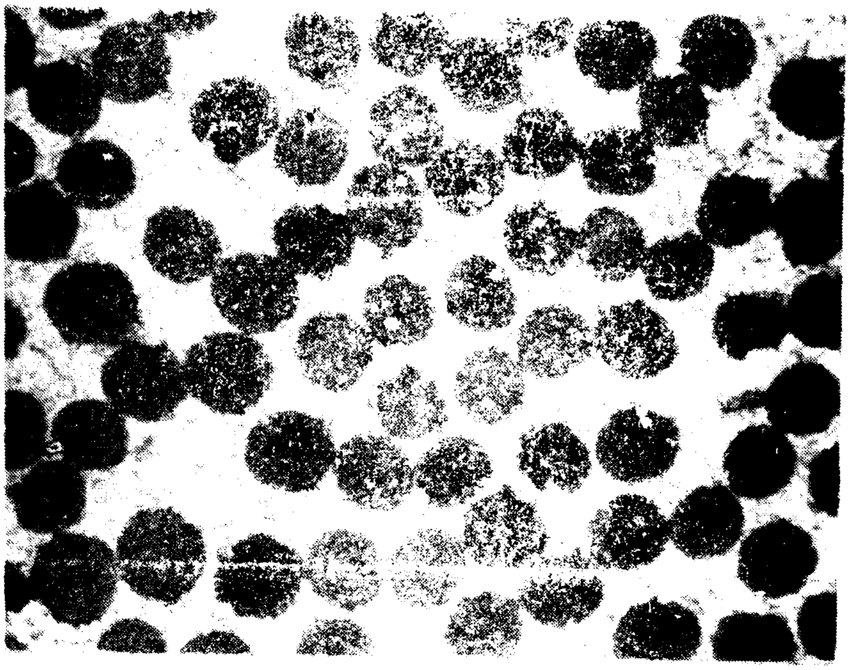

FIGURE [illegible] ED 1000 X

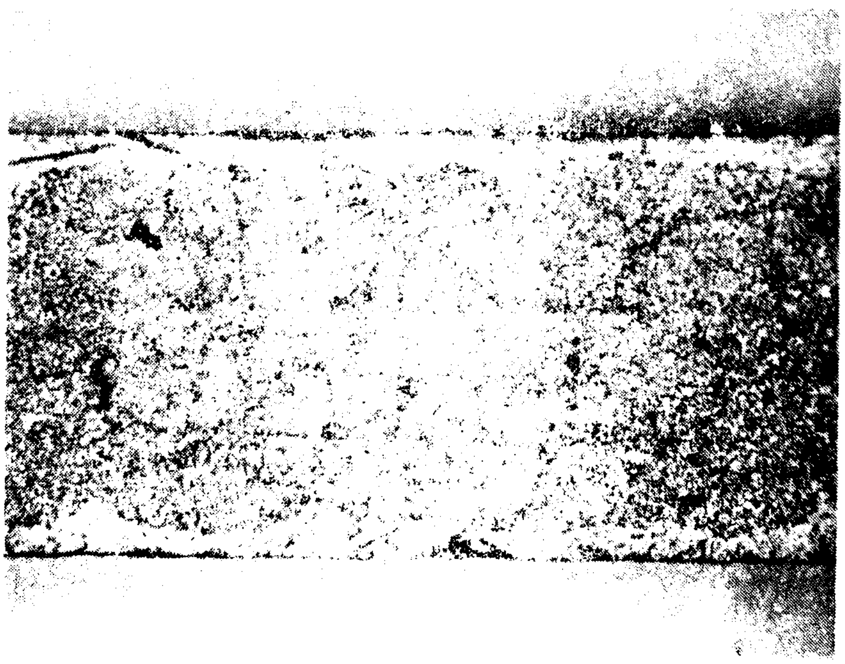

FIGURE [illegible] ED 50 X

DENSITY OF GRAPHITE FIBERS

The density of the graphite fibers was determined by measuring and weighing a prismatic sample of the P55 Gr/Al MMC. Equation (3) was used to calculate the density of the fibers.

Let: L = length = 2.330 inches
t = thickness = 0.04624 inch
w = width = 0.3245 inch
W = weight = 1.378 grams (+ or - 0.002 grams)
D(gr) = density of graphite fibers
D(Al) = density of aluminum = 2.70 grams/cc.
D(gr) = W/[L x t x w x f(gr)] - [1 - f(gr)] x D(Al)]/f(gr)(3)
Density of fibers = 1.96 grams/cc

THEORETICAL MODULUS OF ELASTICITY

The modulus of elasticity of the MMC was determined theoretically by assuming that the elastic modulus of the P55 graphite fibers was 55 million psi. To determine the force required for at the yield stress of the aluminum,

Let: A = cross-sectional area of MMC
E(Al) = elastic modulus of aluminum
E(gr) = elastic modulus of graphite fibers
E = elastic modulus of the metal matrix composite
F = tensile force (load)
S(Al) = stress in aluminum below yielding

For uniaxially oriented fibers,

F = [f(Al) + f(gr) x E(gr) / E(Al)] A x S(Al) (4)
F = 1,117 pounds

for E(Al) = 10.0 million psi, Reference 3.
E(gr) = 55 million psi for pitch 55
S(Al) = 35 ksi at room temperature, Reference 3.
A = 0.0114 square inches

Below the yield stress of the aluminum,

E = E(Al) x f(Al) + E(gr) x f(gr)(5)
E = 28 million psi

Above the yield stress of the aluminum, the contribution to the overall modulus due to the aluminum is so small that,

E = E(gr) x f(gr)(6)
E = 22 million psi

YOUNG'S MODULUS DUE TO A BENT SPECIMEN

When a specimen is bent, its measured elastic modulus in tension appears to be lower than the true elastic modulus. If the bent specimen is assumed to be bent in a circle, then the measured elastic modulus can be calculated from Equation (7). The derivation of this equation is found in Appendix A.

Let:
- E(m) = measured elastic modulus
- E = true elastic modulus of the MMC
- L = length of the test specimen between the grips
- S = stress in the test specimen
- t = thickness of the test specimen
- y = bending displacement at no load, i.e., the displacement between the bent specimen and a straight one at its midsection

$$E(m)/E = 1 - \frac{32y}{32y + t[1 + 4L\,S/(Et)]} \qquad (7)$$

For the MMC specimen having a Young's modulus of 22 million psi and a span of one inch, the ratio of measured modulus to that of the true modulus is shown in Figure 3.

SPECIMEN CONFIGURATIONS

Figure 4 shows two types of specimens to scale. The first type, which appears at the left, consists of a dog-boned shape specimen. This was machined using electrode discharge machining (EDM). The radius of curvature was 1.00 inch between the straight-sided 0.250-inch-wide middle portion of the specimen and the 0.350-inch-wide end portions of the specimen. Each end was one inch long. This shape conforms to ASTM Standards D 3552. Tabs of 5052-T0 aluminum (annealed) were made such that there was a 10-degree taper. The tab thickness was 0.062 inch and they had a width of 0.350 inch and a length of one inch. The second type specimen was a straight-sided specimen shown to the right in the figure. These were machined using a fine cut end mill with final lapping on 600 silicon carbide paper on a glass plate.

Both types of specimens were bonded with the aluminum tabs. The tab width was 0.250 inch for the straight-sided specimens. Bonding was done with two part Miller-Stephenson Epoxy 907 with a bonding shear strength of 2500 psi or greater. Curing was done at room temperature for 24 hours. Figure 5 shows bonded dog-boned specimens, see the two left specimens in the photograph. Figure 6 shows bonded straight-sided specimens. Figure 7 shows straight-sided specimens except that the tab width was 0.350 inch. Figure 8 shows dog-boned specimens with a radius of curvature of 0.250 inch at the end of the gauge length region.

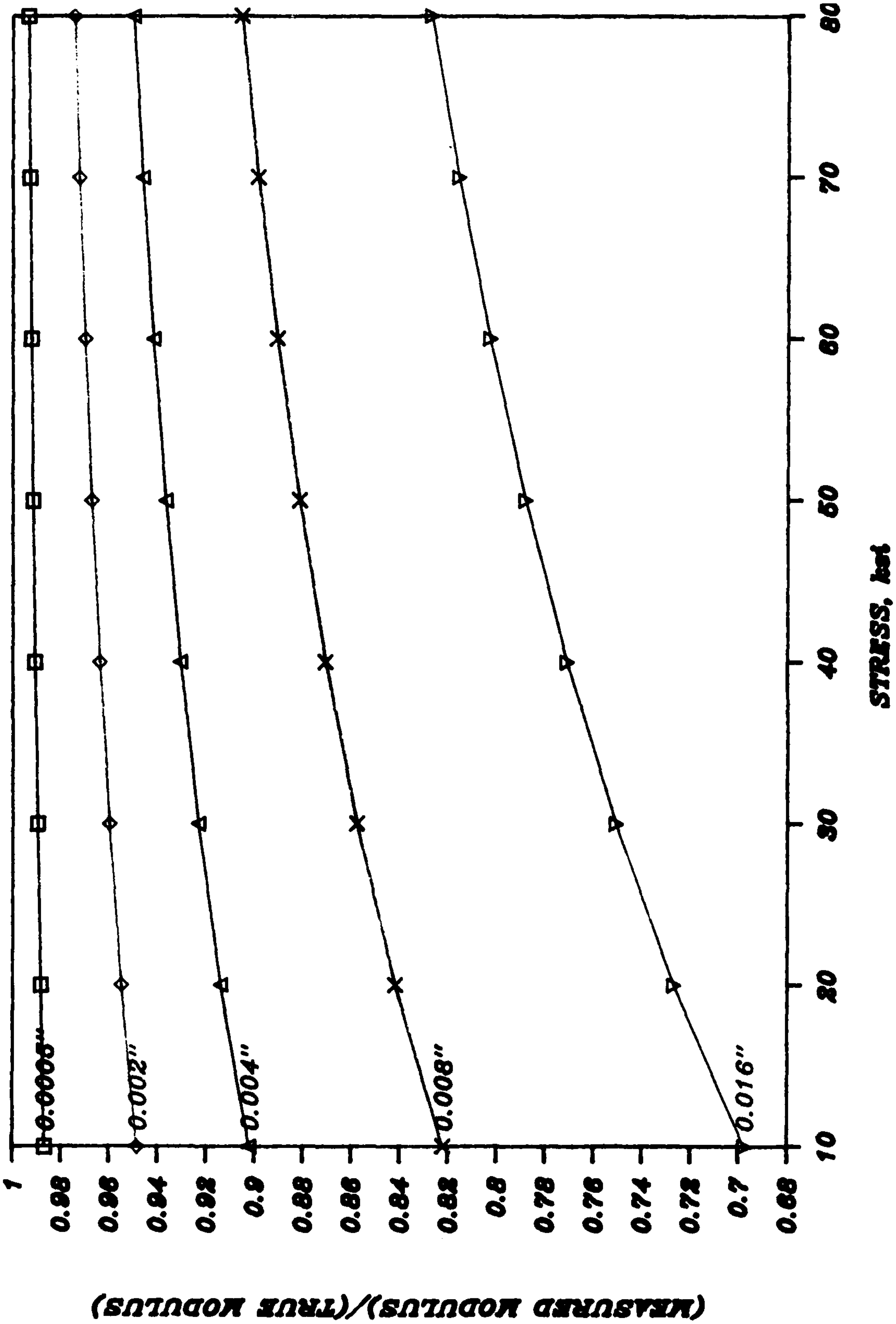

FIGURE 3. BENT SPECIMEN EFFECT ON ELASTIC MODULUS

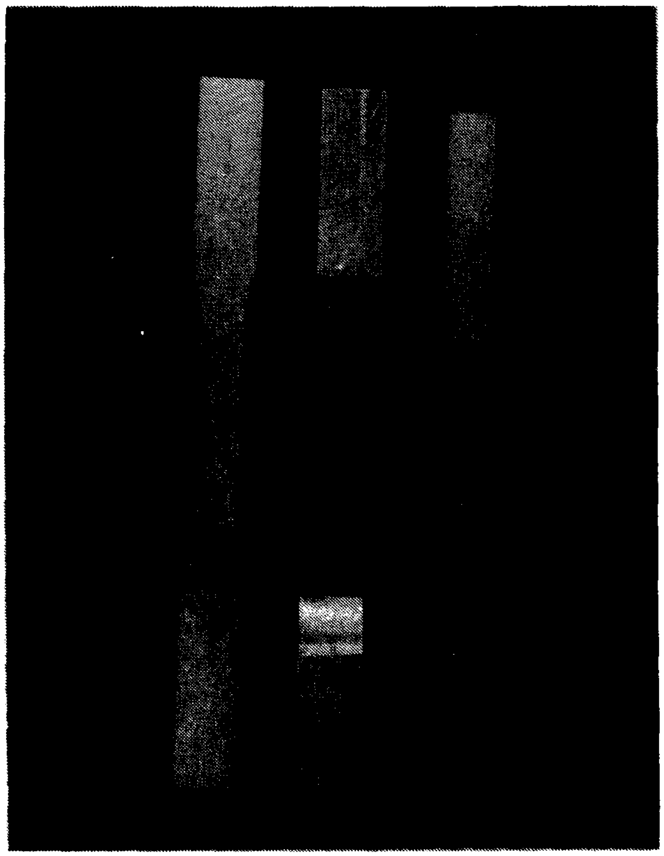

FIGURE 4. DOG-BONED AND STRAIGHT-EDGE SPECIMENS P55 GR/AL WITH ALUMINUM TABS PRIOR TO ASSEMBLY

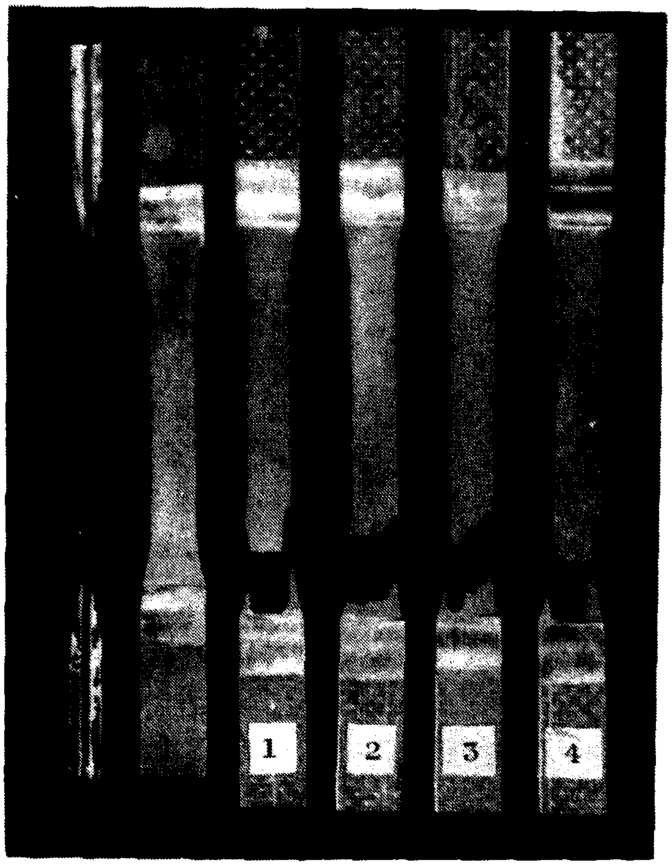

FIGURE 5. P55 GR/AL DOG-BONED 1-INCH RADIUS, TESTED AT 293K

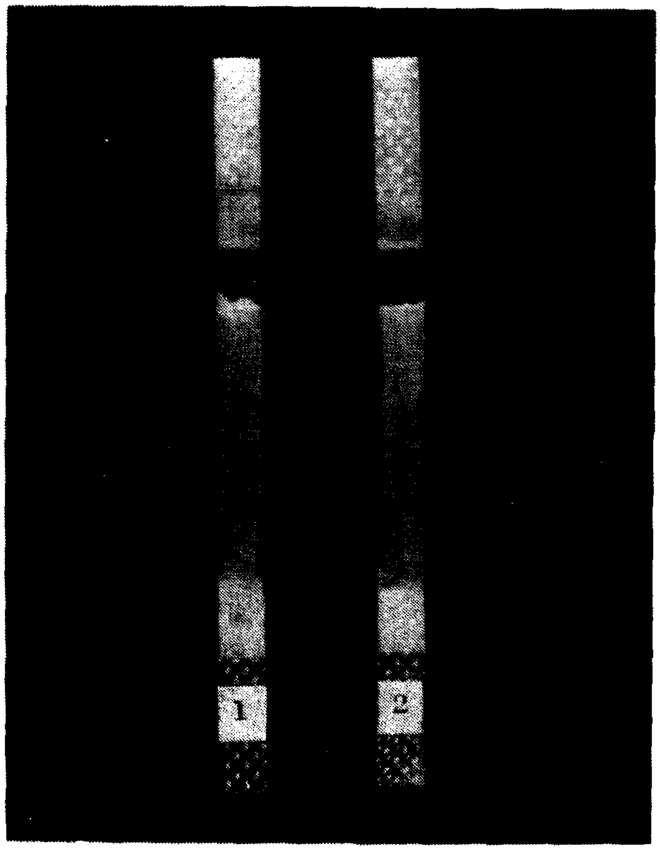

FIGURE 6. P55 GR/AL STRAIGHT SIDES, FLUSH TABS, TESTED 295K

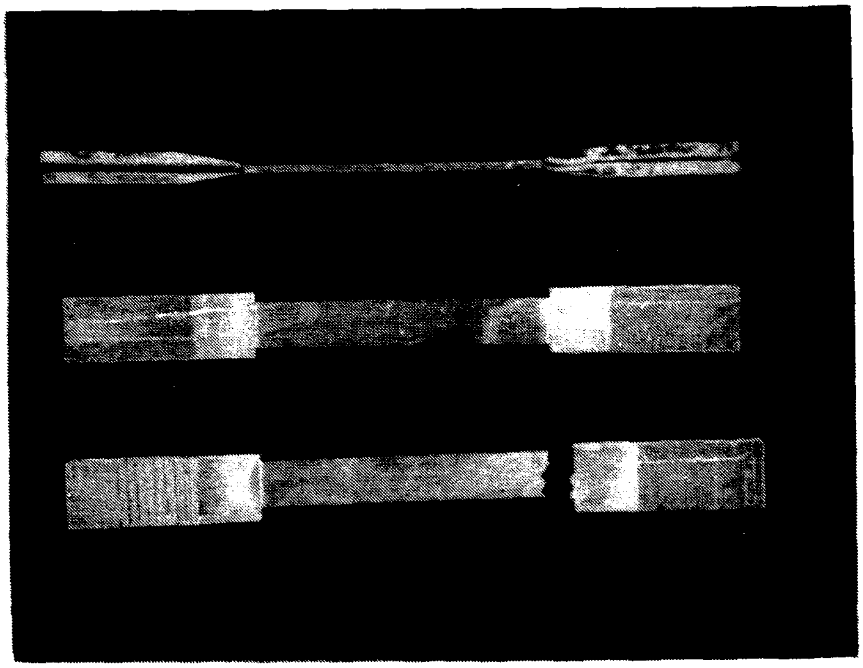

FIGURE 7. P55 GR/AL STRAIGHT SIDES, LARGE TABS, 293K TESTS

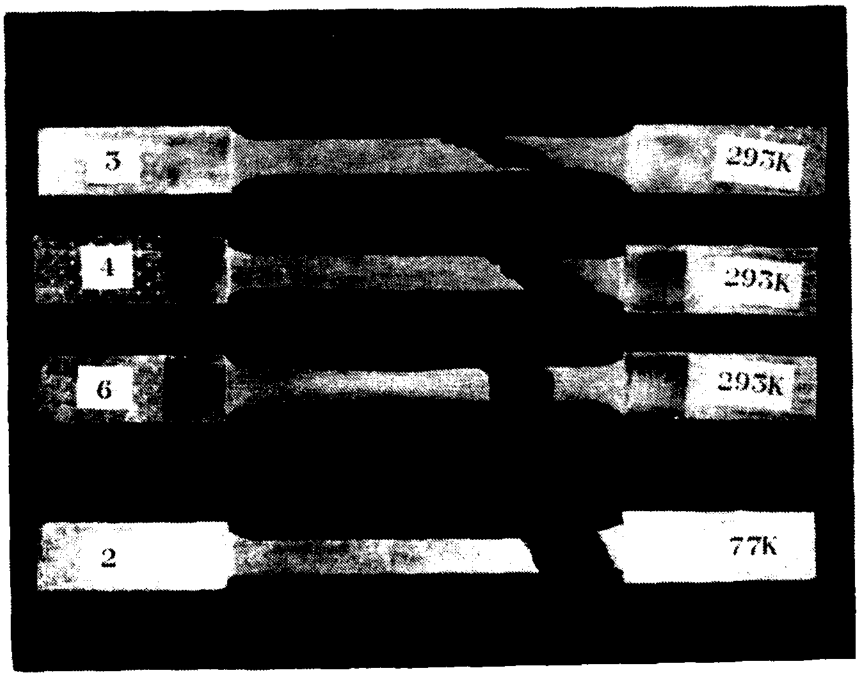

FIGURE 8. P55 GR/AL DOG-BONED 1/4 INCH RADIUS SPECIMENS TESTED AT 77K AND 293K

TENSILE TESTING

Dog-Boned 1-Inch-Radius Tensile Specimens Tested at 293K

Tensile tests using dog-boned type specimens with one-inch radius, see Figure 4, are summarized in Table 1. The fractured specimens are shown in Figure 5. Note that fracture began at the outer sides of the specimens where the radius of curvature is tangent to the straight sides of the specimens. Here, the stress concentration increases the stress by about 5 percent over the nominal stress, Reference 4. Because of the high elastic energy stored in the curved portion from the point of fracture initiation "initial crack" to the tabs, this energy is relaxed by shear parallel to the fibers. Thus, the crack then propagates parallel to the fibers until the crack meets the tabs. Fracture then continues along or parallel to the tab.

The load-elongation curves for the tests are shown in Figures 9 through 14. Elastic modulus measurements were made in the middle third of the elastic curve. In each of the figures, the beginning position of the modulus measurement is shown as a "b" while the end position is shown as an "m." The calculated modulus is the least squares straight line fit of all data points between "b" and "m." The average value of the modulus is 18.2 million psi., while the ultimate tensile strength is 82.3 ksi in Figure 3. The true ultimate tensile strength is probably 5 percent higher or about 86.4 ksi.

Straight Sides Tensile Specimens, Flush Tabs, Tested at 295K

Table 2 shows the results of tensile testing specimens with straight sides and flush tabs. These type specimens are also shown in Figure 4. The fractured specimens are shown in Figure 6. Here, the modulus of elasticity is 21.7 million psi while the tensile strength is 82 ksi. Note how close the modulus is to the theoretically calculated one of 22 million psi. This is quite close to the same results obtained from the 1 inch radius dog-boned specimens. Figures 15 and 16 show the load elongation curves for these specimens.

Straight Sides Tensile Specimens, Large Tabs, Tested at 293K

These specimens broke at the tabs as shown in Figure 7. The test statistics are given in Table 3, while the load elongation curves are shown in Figures 17 through 22. Here, the elastic modulus averaged 18.3 million psi while the ultimate tensile strength averaged 72.8 ksi. The reason for the lower tensile strength is due to the stress concentrations caused by the larger tabs which create a sharp corner at the edge of the specimen where the tab meets the specimen. Note the fracture along the tab line.

Specimens With Large Tabs Tested at 77K

Figure 8 shows a dog-boned specimen with a 1/4-inch radius of curvature tested at 77K. This was test number 2 given in Table 4 and shown as Figure 23. Fracture may have started either at the tab where there is a large stress concentration or at the point where the curvature is tangent to the straight edge of the specimen. Here the stress concentration was calculated to be about 12 percent higher stress than the nominal stress. Test number 1 was a specimen with straight sides and large tabs.

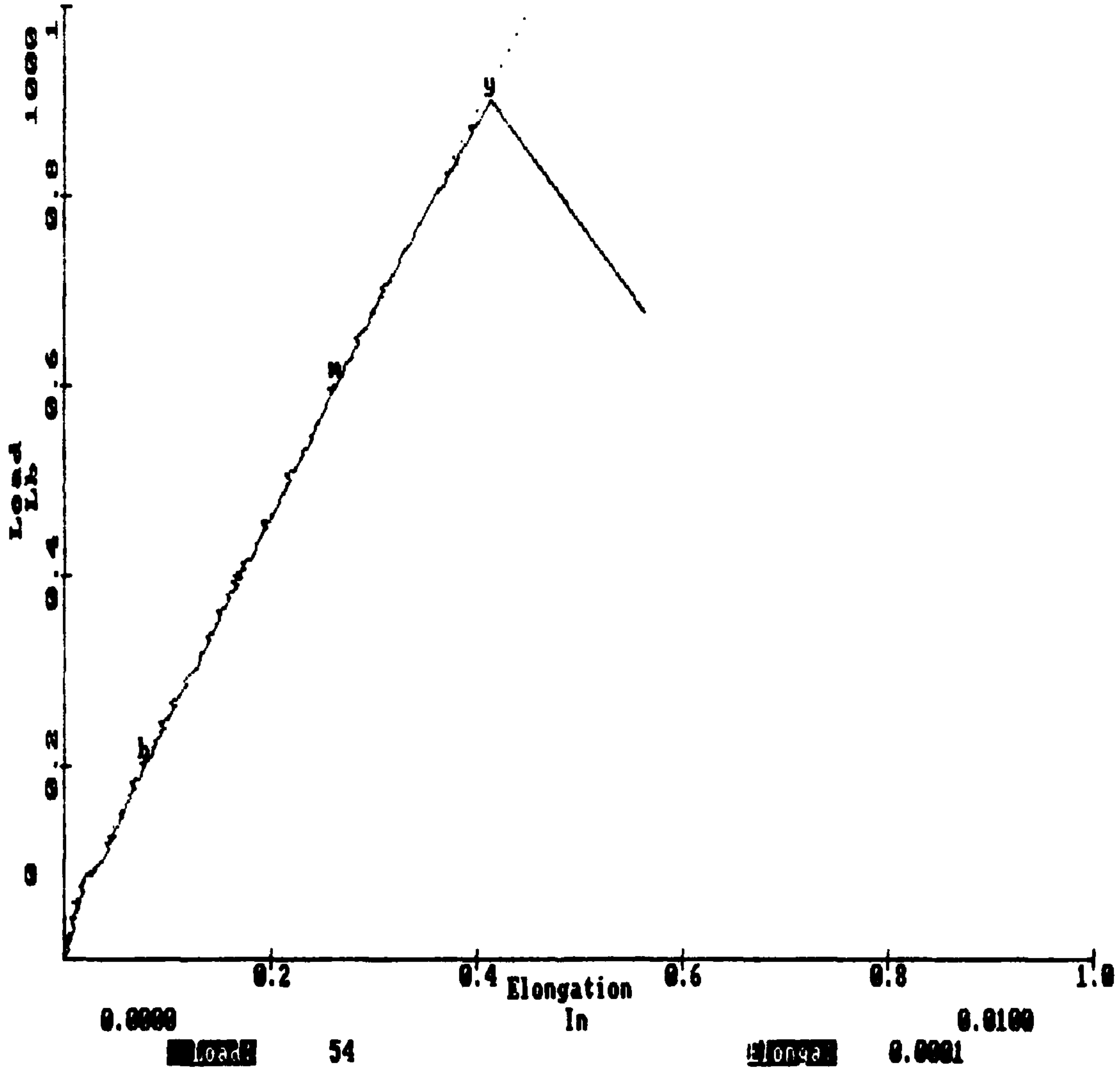

FIGURE 9. BATCH NUMBER: P55 AL/GR. 293K SPECIMEN NO: 1

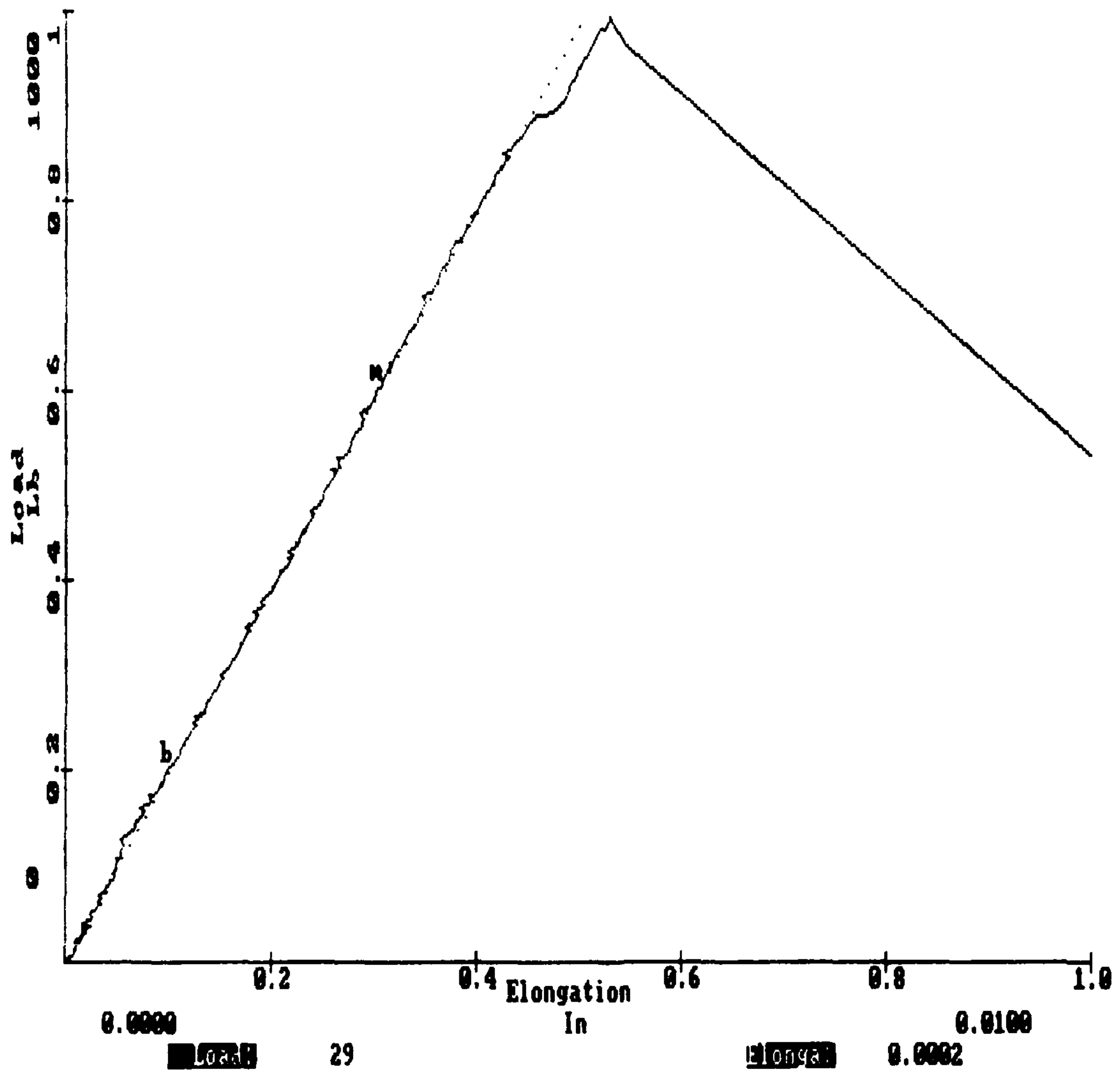

FIGURE 10. BATCH NUMBER: P55 AL/GR. 293K SPECIMEN NO: 2

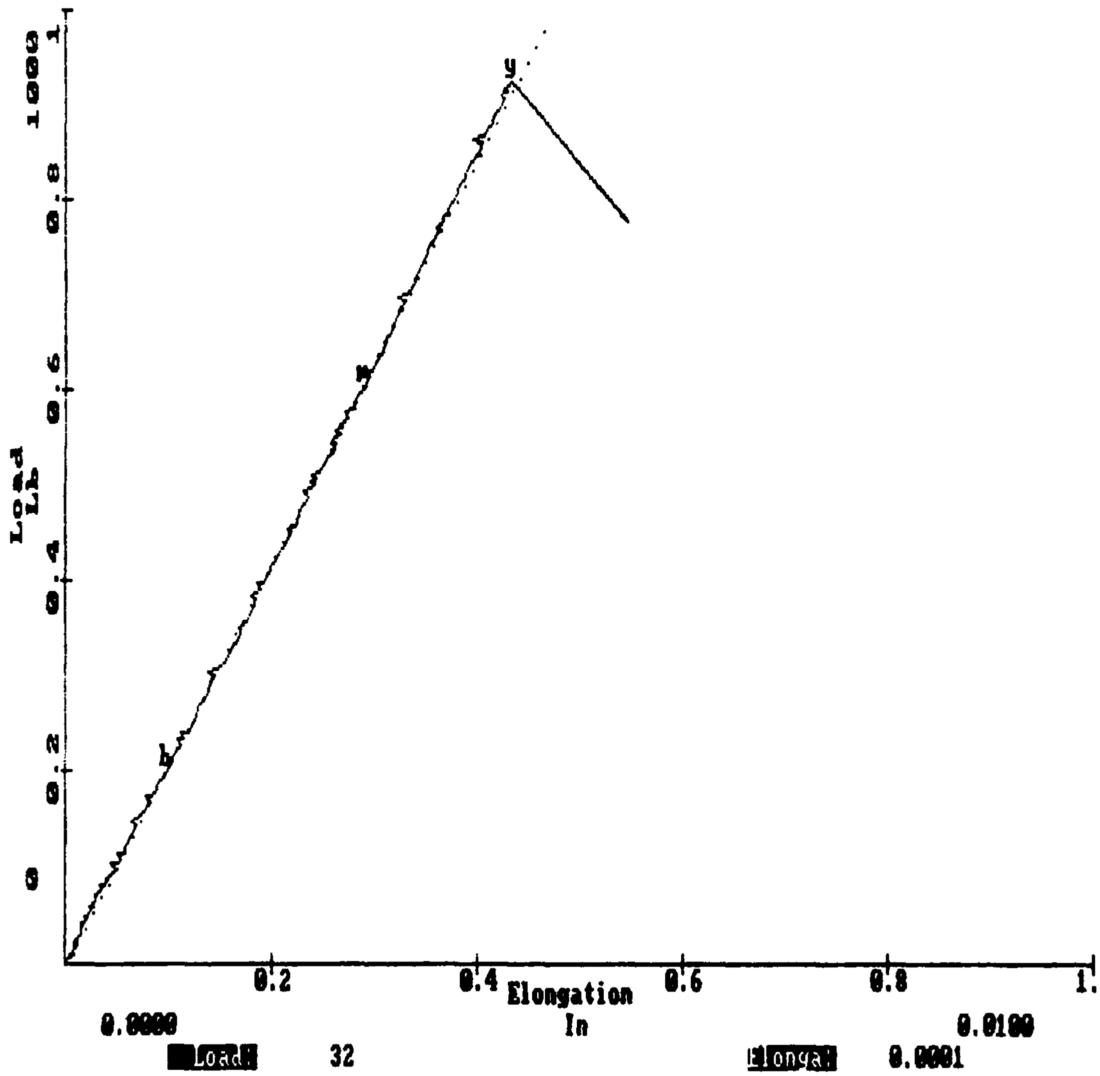

FIGURE 11. BATCH NUMBER: P55 AL/GR. 293K SPECIMEN NO: 3

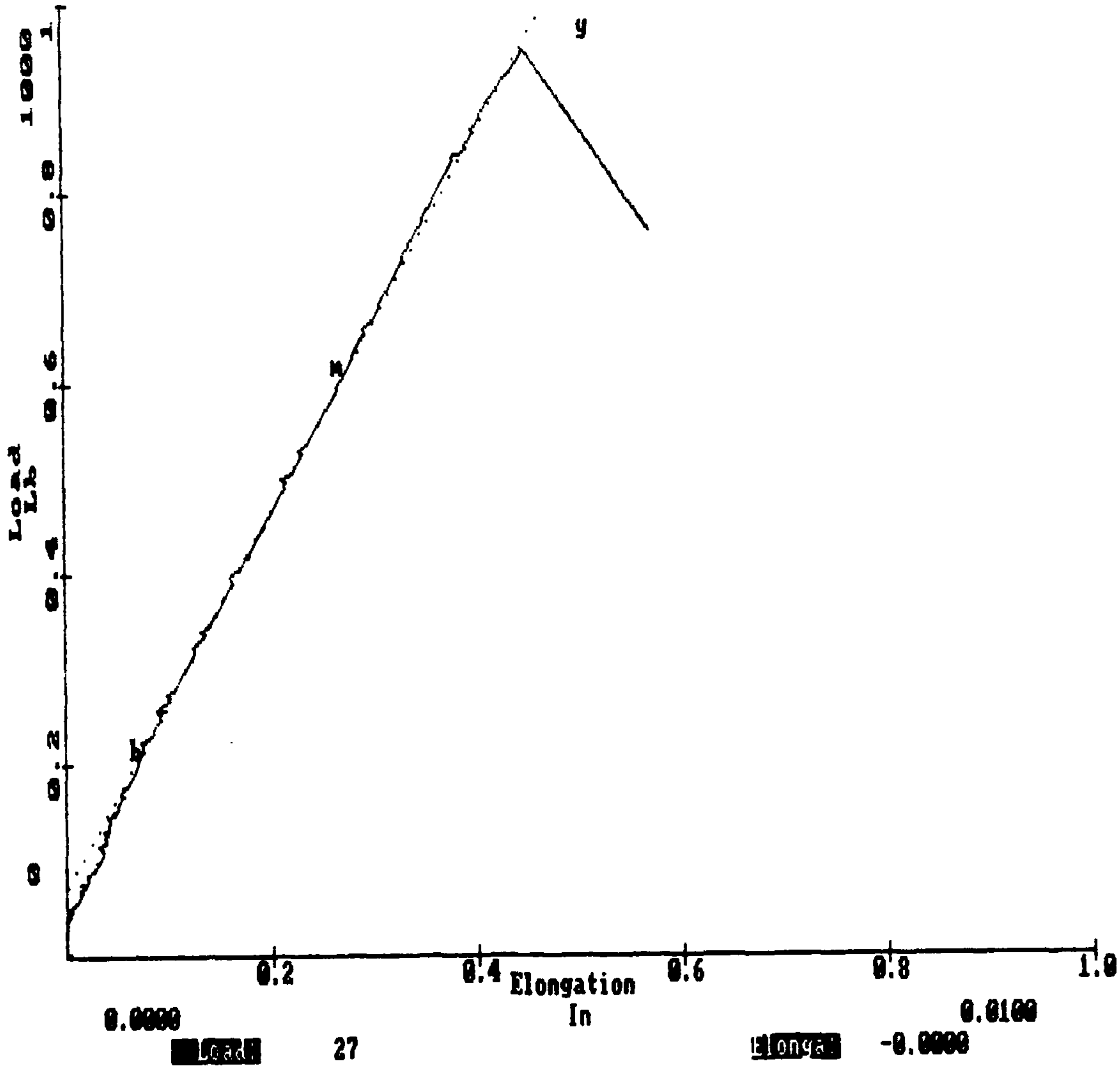

FIGURE 12. BATCH NUMBER: P55 AL/GR. 293K SPECIMEN NO: 4

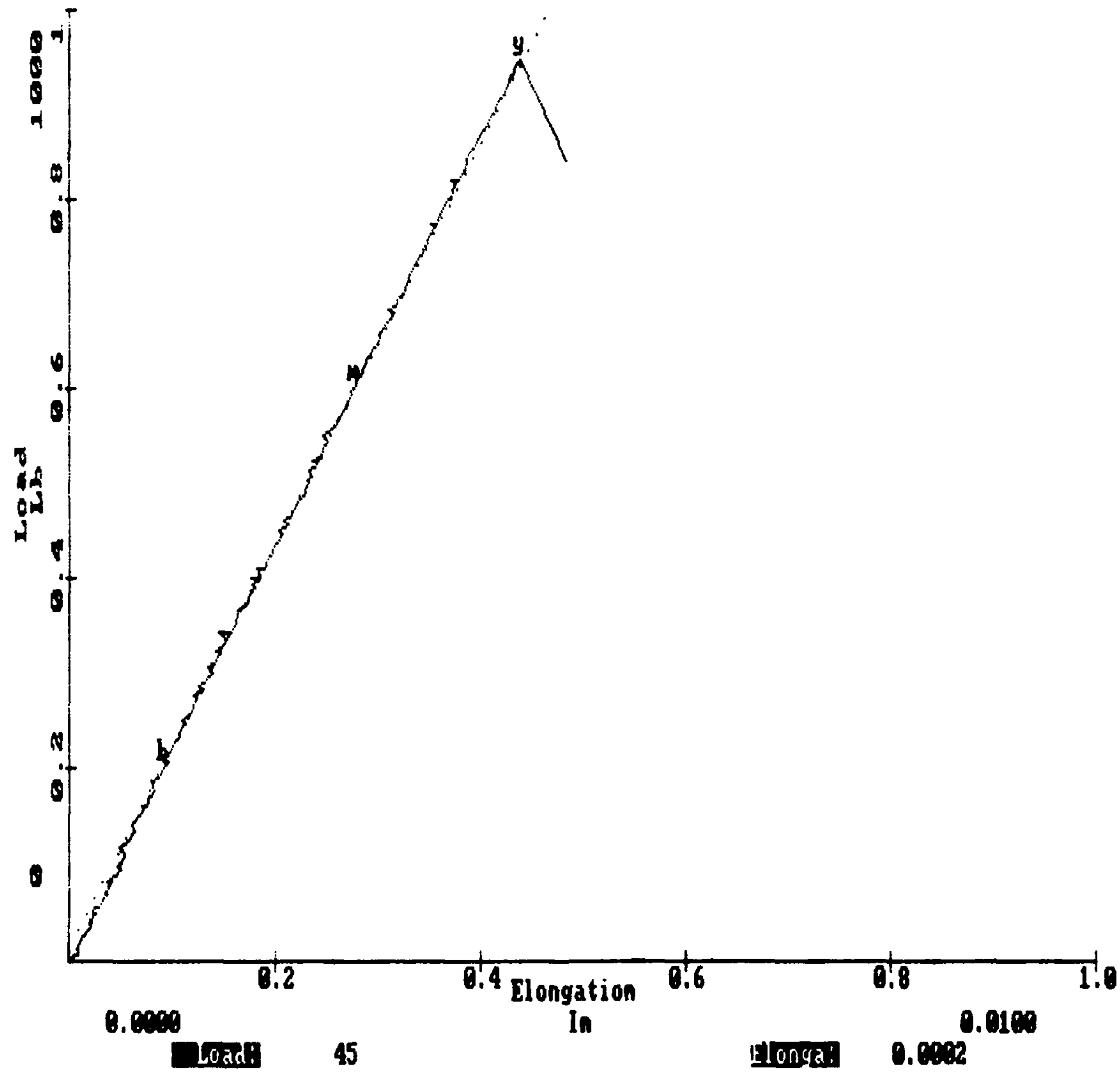

FIGURE 13. BATCH NUMBER: P55 AL/GR. 293K SPECIMEN NO: 5

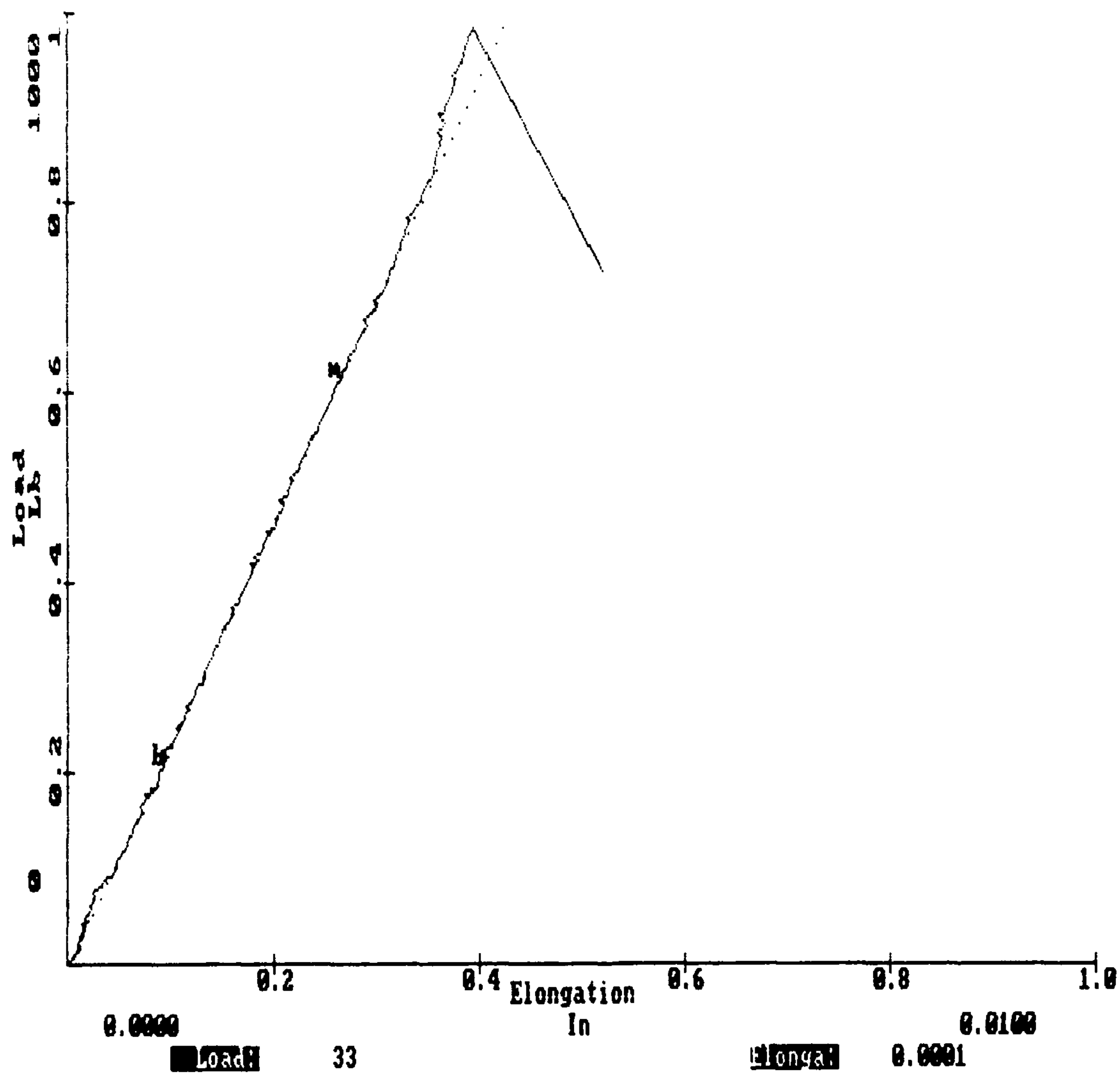

FIGURE 14. BATCH NUMBER: P55 AL/GR. 293K SPECIMEN NO: 6

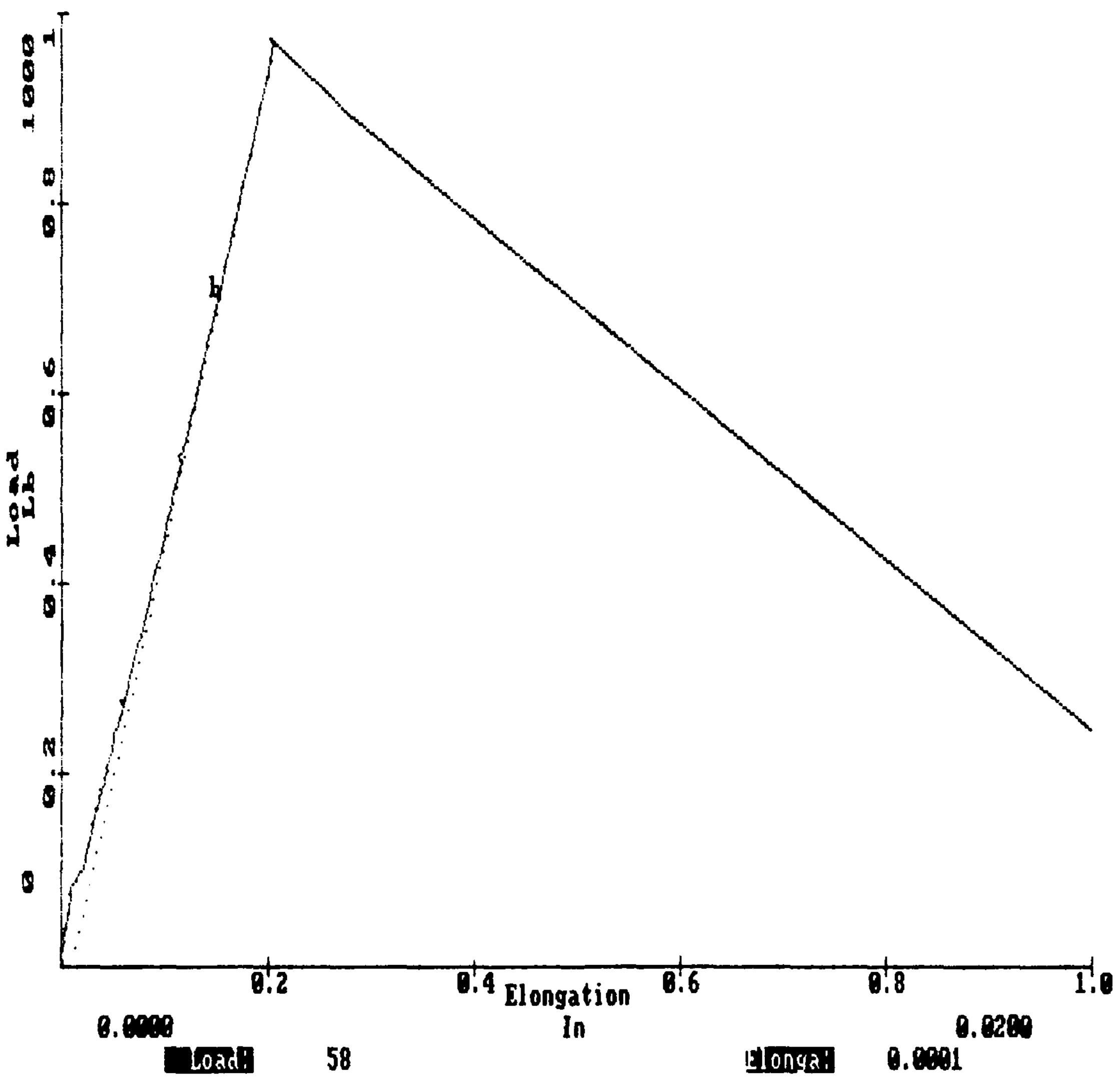

FIGURE 15. BATCH NUMBER: P55 AL/GR. 295K SPECIMEN NO: 1

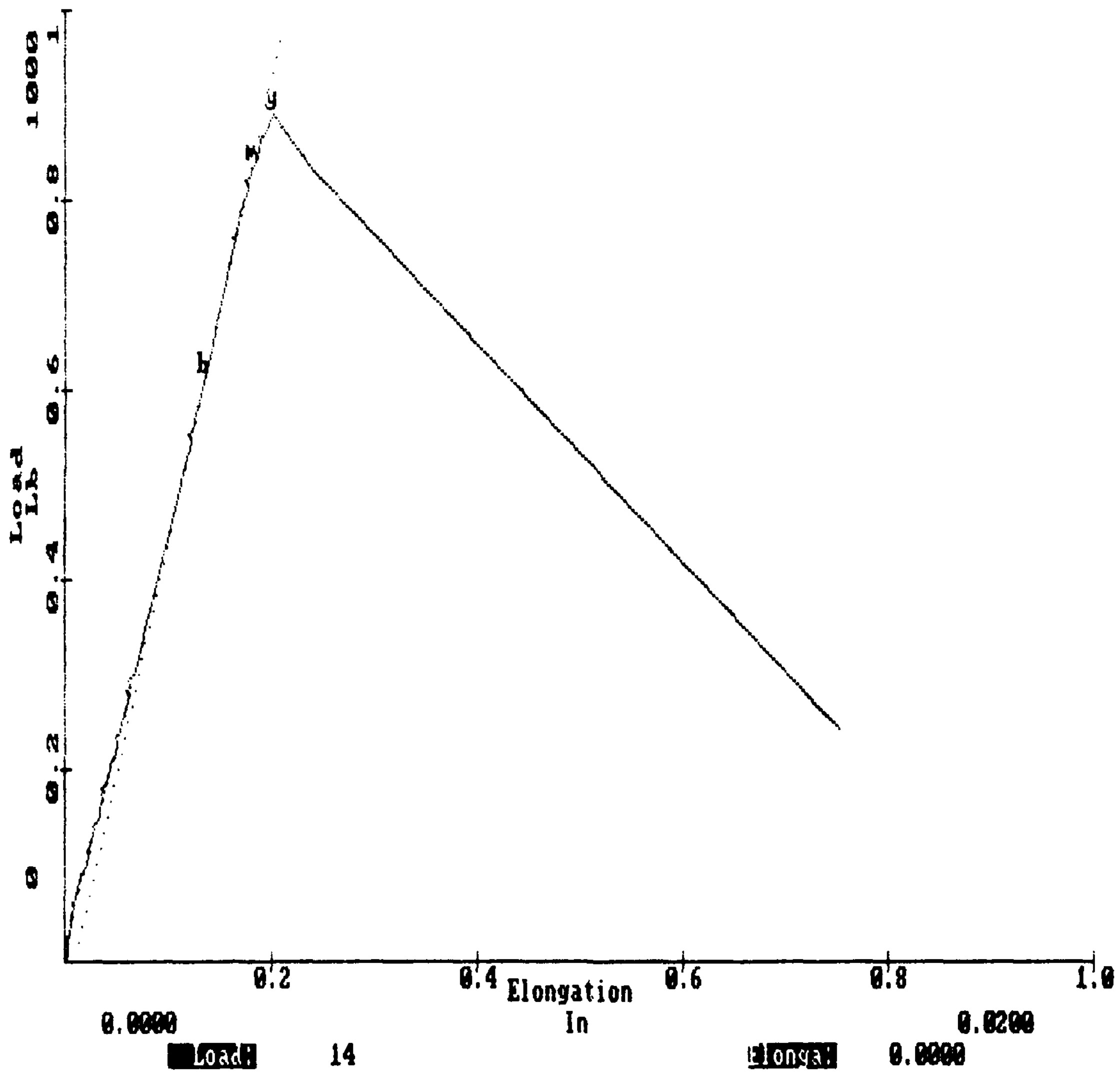

FIGURE 16. BATCH NUMBER: P55 AL/GR. 295K SPECIMEN NO: 2

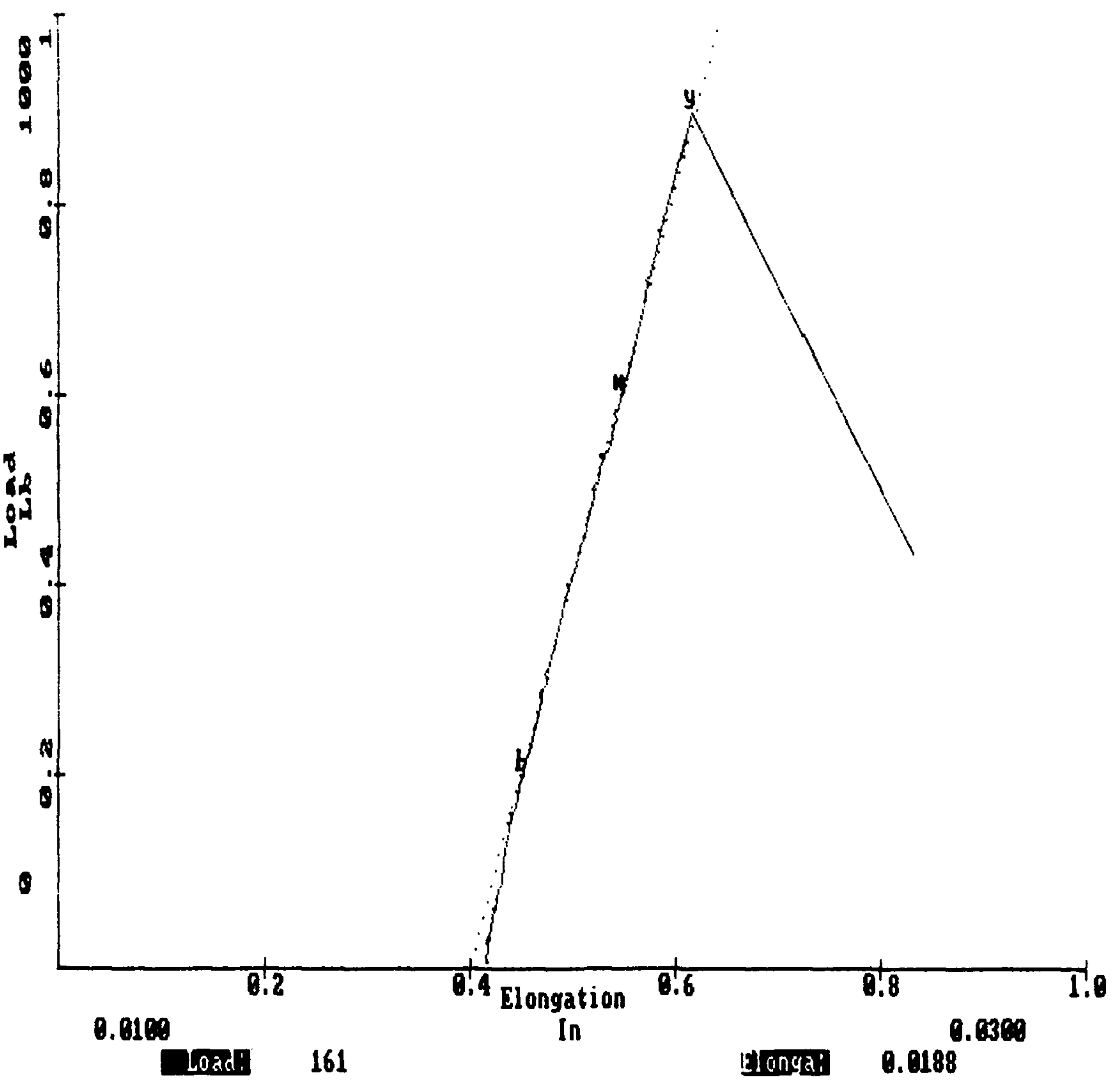

FIGURE 17. BATCH NUMBER: AL-COMPOS. 293K SPECIMEN NO: 1

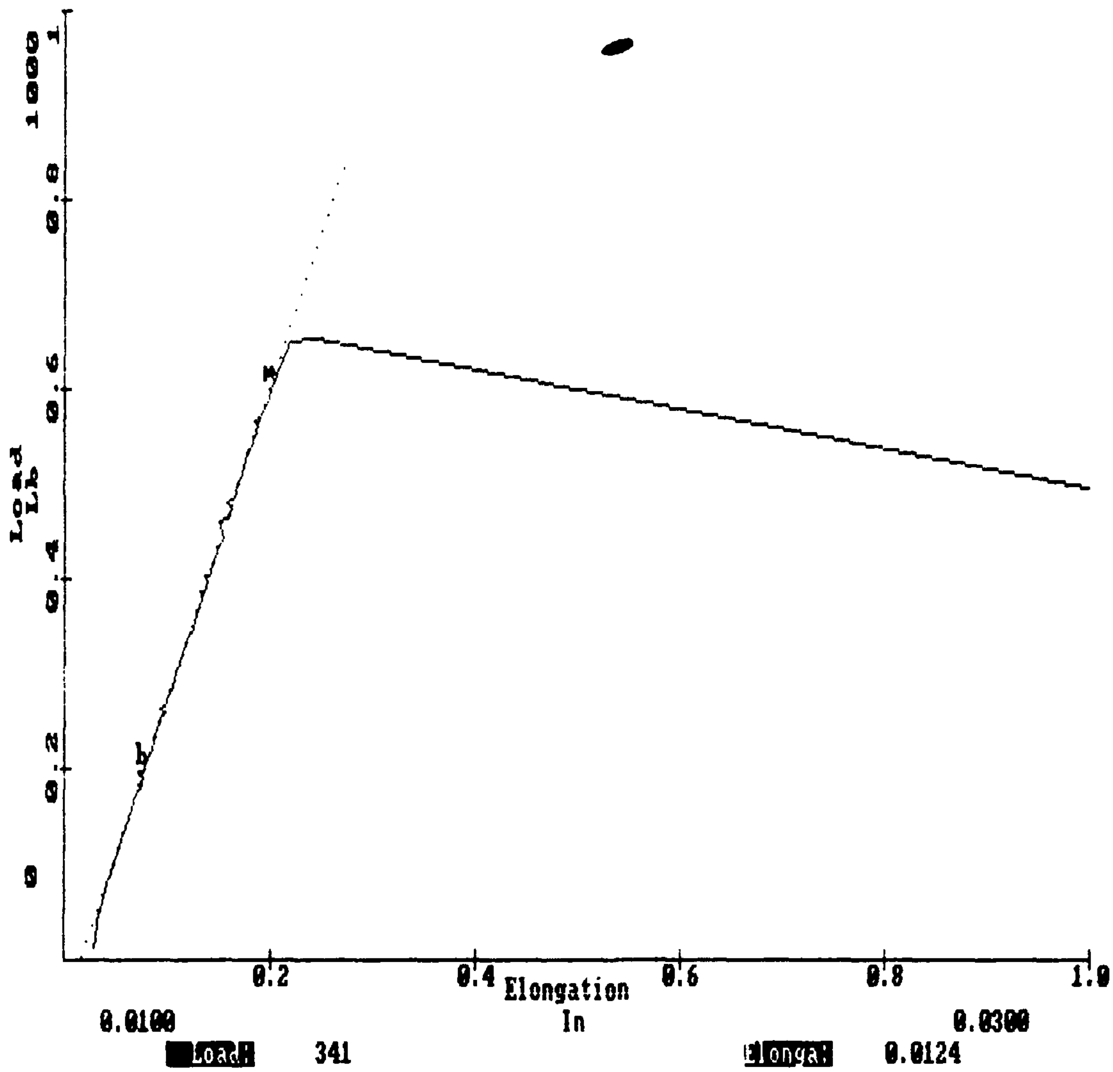

FIGURE 18. BATCH NUMBER: AL COMPOS. 293K SPECIMEN NO: 2

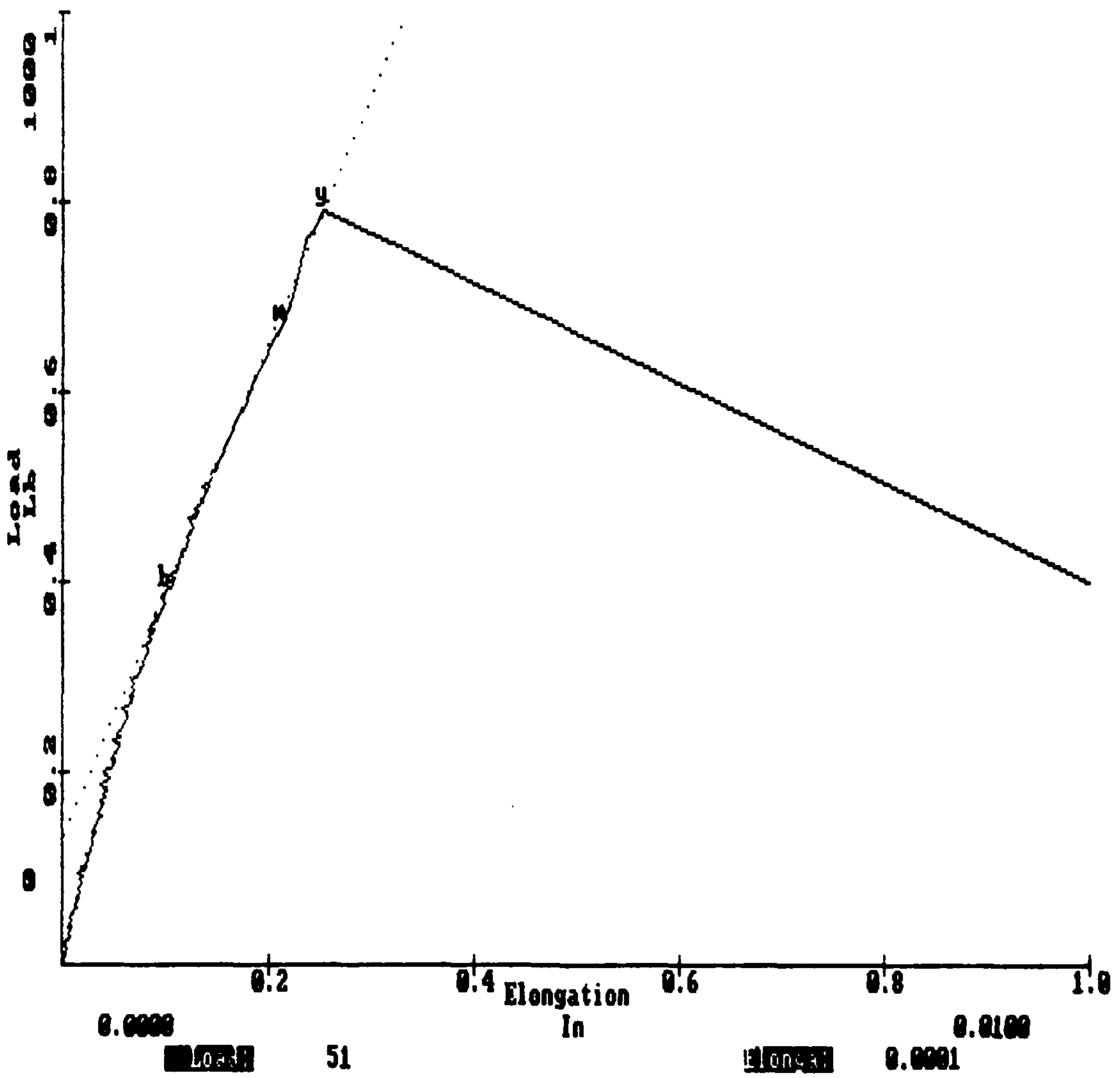

FIGURE 19. BATCH NUMBER: AL COMPOS. 293K SPECIMEN NO: 3

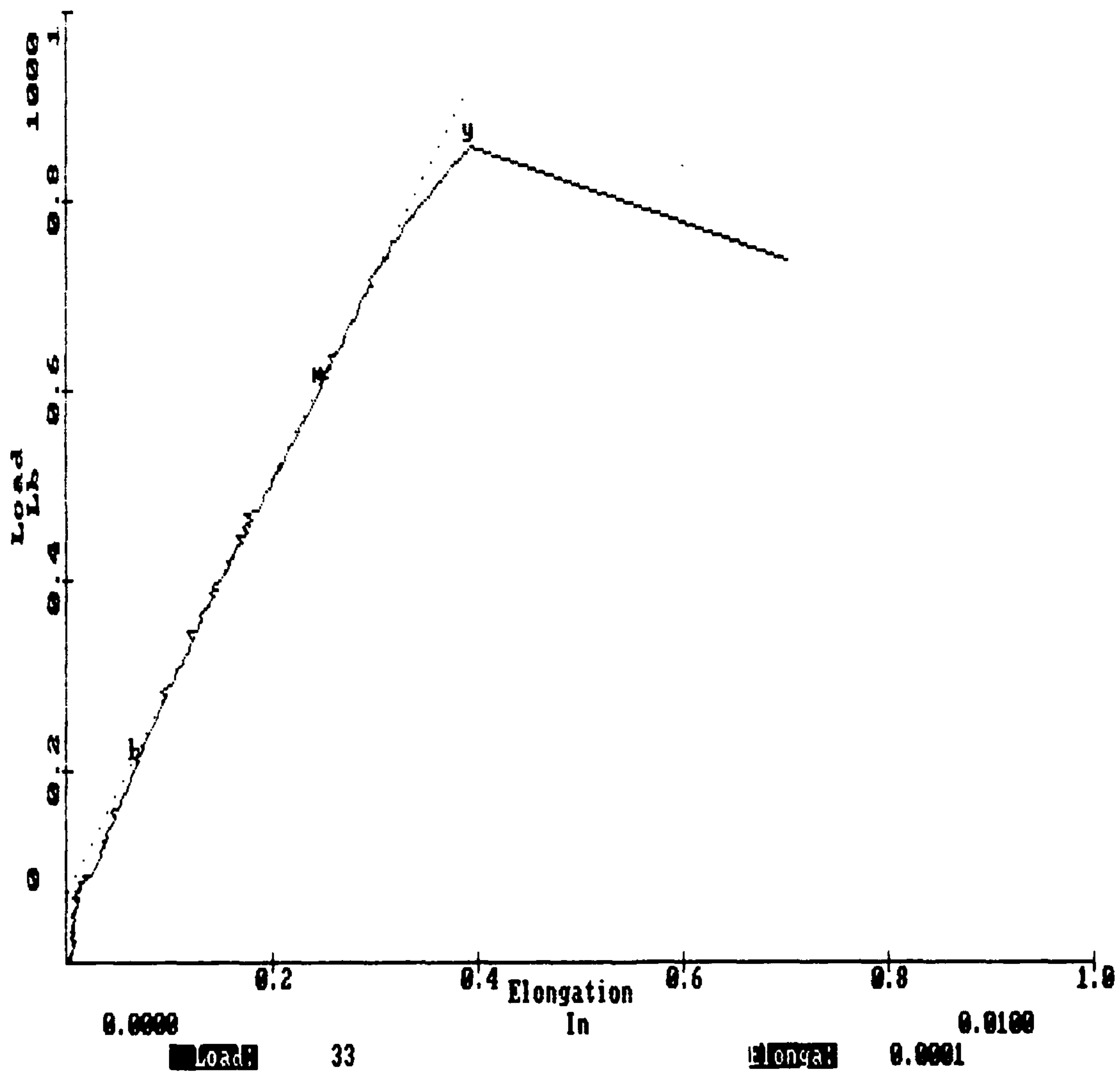

FIGURE 20. BATCH NUMBER: AL COMPOS. 293K SPECIMEN NO: 4

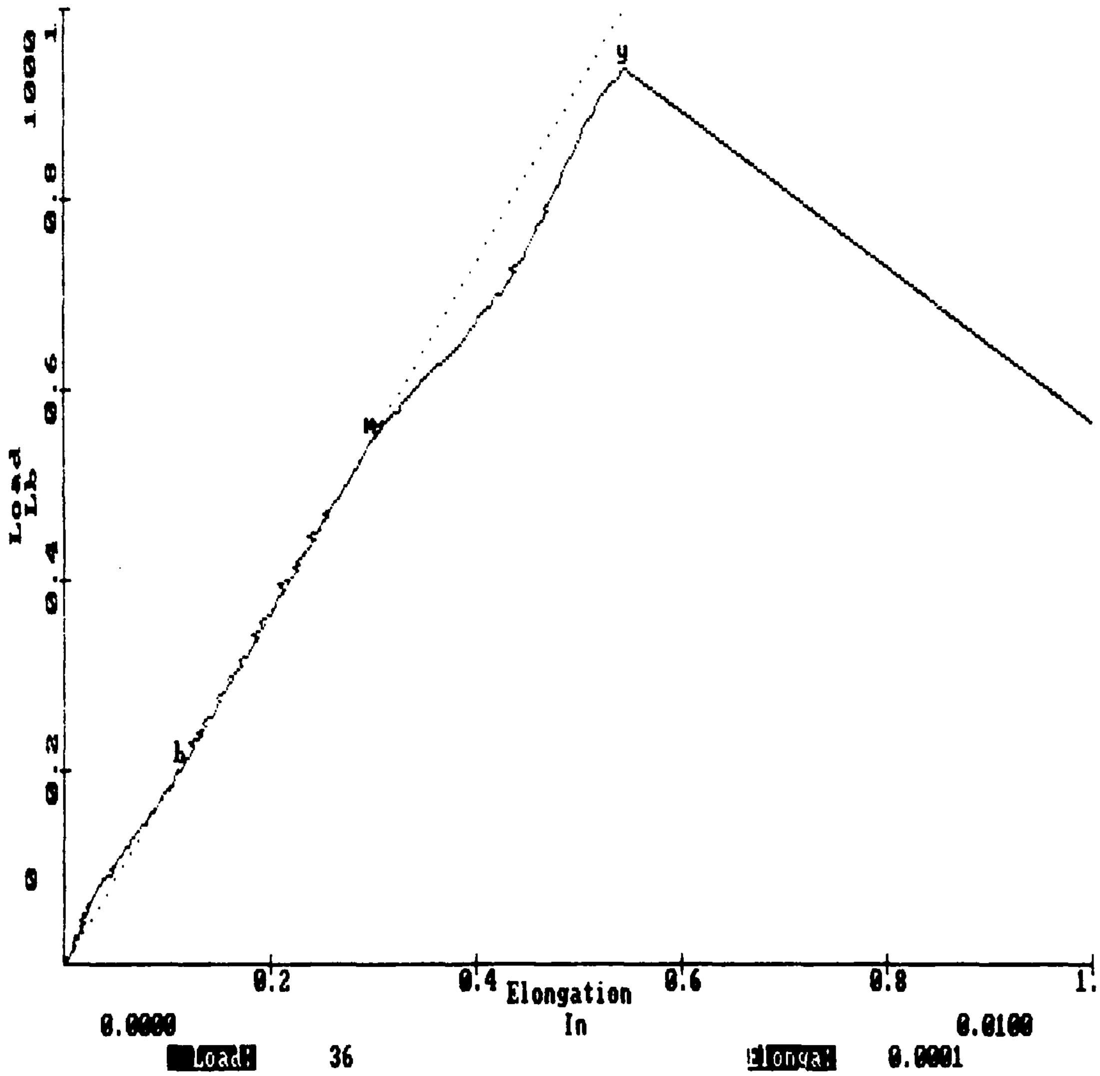

FIGURE 21. BATCH NUMBER: AL-COMPOS. 293K SPECIMEN NO: 5

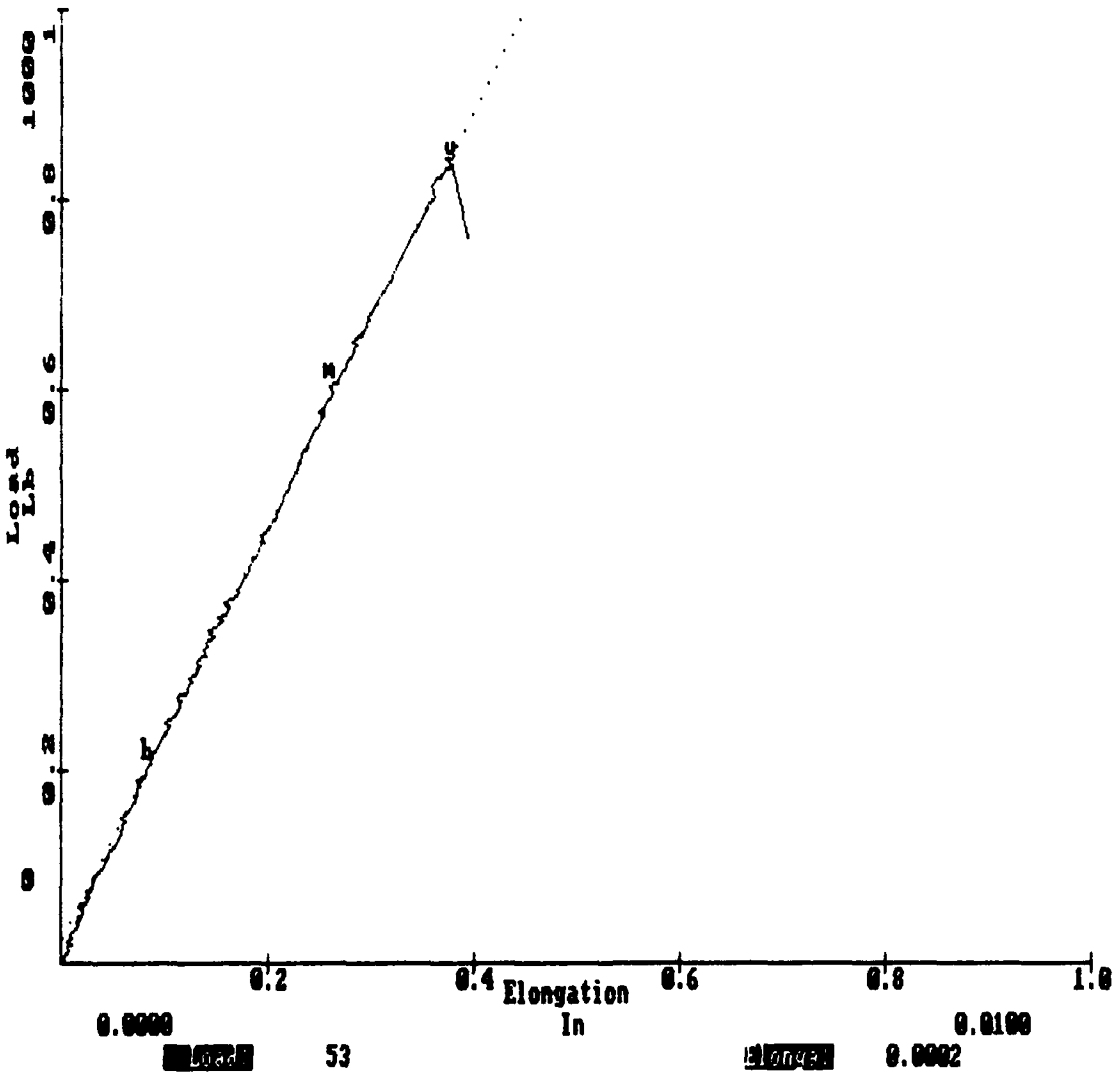

FIGURE 22. BATCH NUMBER: AL COMPOS. 293K SPECIMEN NO: 6

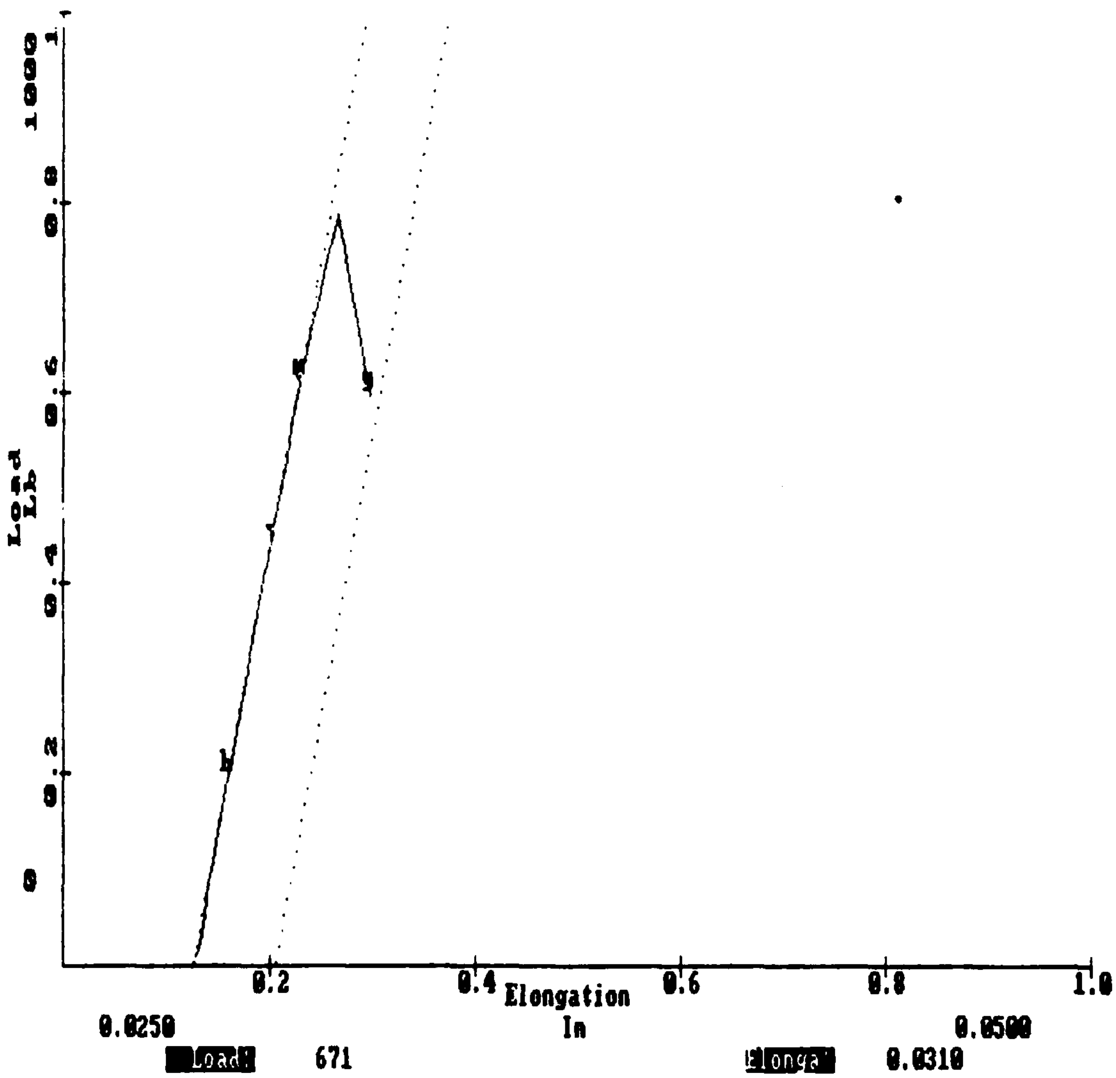

FIGURE 23. BATCH NUMBER: AL COMPOS. 77K SPECIMEN NO: 2

TABLE 1. P55 GR/AL DOG BONES 1-INCH RADIUS, TESTED AT 293K

ADVANCED MATLS. LAB

Concord, MA

Tensile Test

Batch Number: P55 Al/gr.293K
Date: 08-18-88 Number of Specimens : 6

Operator I.D. :............... TA
Storage Disk No. :.............1
Comments :....................Dog bone specimen

TEST RESULTS

	Thick./Dia In	Width In	Peak Load Lb	U.T.Stngth PSI	Yld Stngth PSI	Yld Elong. %	Brk Stngth PSI	Brk Elong. %	Modulus PSI	Energy Ft-Lb
1	0.046	0.250	899.442	786.628E+02	786.628E+02	0.433	786.628E+02	0.433	185.256E+05	0.262
2	0.046	0.251	991.962	863.421E+02	863.421E+02	0.520	837.934E+02	0.545	171.498E+05	0.614
3	0.046	0.251	923.076	793.033E+02	793.033E+02	0.430	793.033E+02	0.430	181.929E+05	0.244
4	0.045	0.250	951.271	839.131E+02	844.505E+02	0.545	839.131E+02	0.486	174.500E+05	0.278
5	0.046	0.250	947.210	817.997E+02	817.997E+02	0.445	817.997E+02	0.445	182.394E+05	0.207
6	0.047	0.249	984.459	840.429E+02	840.429E+02	0.392	840.429E+02	0.392	196.954E+05	0.241

STATISTICS

	Thick./Dia In	Width In	Peak Load Lb	U.T.Stngth PSI	Yld Stngth PSI	Yld Elong. %	Brk Stngth PSI	Brk Elong. %	Modulus PSI	Energy Ft-Lb
Mean	0.046	0.250	949.573	823.440E+02	824.335E+02	0.462	819.130E+02	0.455	182.422E+05	0.308
Min	0.045	0.249	899.442	786.628E+02	786.628E+02	0.392	786.628E+02	0.392	171.498E+05	0.207
Max	0.047	0.251	991.962	863.421E+02	863.421E+02	0.545	840.429E+02	0.545	196.954E+05	0.614
St.Dev	0.001	0.001	35.325	298.081E+01	304.477E+01	0.061	242.717E+01	0.053	962.396E+03	0.152
% C.V.	1.334	0.414	3.720	3.620	3.694	13.140	2.963	11.593	5.279	49.426

TEST CONDITIONS

Crosshead Speed :..............	0.1	In/Min
Load Cell Capacity :...........	5000	Lb
Threshold :....................	5	% Of FSL
Break Criterion :..............	95	%
Extensometer Used :............	1	1:Y,0:N
Gage Length :..................	1.00	In
Action @ End Of Test :.........	1	1:St,0:Rtn
Crosshead Direction :..........	1	1:Up,0:Dn
Yield(Zero,Offset) :...........	0.0	0:Z,1:Off
Offset At Yield :..............	0.2	%

TABLE 2. P55 GR/AL STRAIGHT SIDES, FLUSH TABS, TESTED 295K

ADVANCED MATLS. LAB

Concord, MA

Tensile Test

Batch Number: P55 gr/Al.295K
Date: 09-02-88

Number of Specimens : 2

Operator I.D. :................ TA
Storage Disk No. :.............1
Comments :....................Straight sides & tab

TEST RESULTS

	Thick./Dia In	Width In	Peak Load Lb	U.T.Stngth PSI	Yld Stngth PSI	Yld Elong. %	Brk Stngth PSI	Brk Elong. %	Modulus PSI	Energy Ft-Lb
1	0.046	0.249	972.032	850.347E+02	850.347E+02	0.384	778.757E+02	0.543	216.712E+05	0.965
2	0.045	0.248	889.532	790.368E+02	790.368E+02	0.383	741.302E+02	0.457	217.395E+05	0.670

STATISTICS

	Thick./Dia In	Width In	Peak Load Lb	U.T.Stngth PSI	Yld Stngth PSI	Yld Elong. %	Brk Stngth PSI	Brk Elong. %	Modulus PSI	Energy Ft-Lb
Mean	0.046	0.248	930.782	820.358E+02	820.358E+02	0.383	760.030E+02	0.500	217.054E+05	0.817
Min	0.045	0.248	889.532	790.368E+02	790.368E+02	0.383	741.302E+02	0.457	216.712E+05	0.670
Max	0.046	0.249	972.032	850.347E+02	850.347E+02	0.384	778.757E+02	0.543	217.395E+05	0.965
St.Dev	0.000	0.000	58.336	424.118E+01	424.118E+01	0.001	264.846E+01	0.061	482.265E+02	0.209
% C.V.	0.928	0.171	6.267	5.170	5.170	0.276	3.485	12.160	0.223	25.528

TEST CONDITIONS

Crosshead Speed :..............	0.1	In/Min
Load Cell Capacity :...........	5000	Lb
Threshold :....................	5	% Of FSL
Break Criterion :..............	50	%
Extensometer Used :............	1	1:Y,0:N
Gage Length :..................	1.00	In
Action @ End Of Test :.........	1	1:St,0:Rtn
Crosshead Direction :..........	1	1:Up,0:Dn
Yield(Zero,Offset) :...........	0.0	0:Z,1:Off
Offset At Yield :..............	0.2	%

TABLE 3. P55 GR/AL STRAIGHT SIDES, LARGE TABS, TESTED AT 293K

ADVANCED MATLS. LAB

Concord, MA

Tensile Test

Batch Number: Al COMPOS.293K
Date: 04-03-87 Number of Specimens : 6

Operator I.D. :............... TA
Storage Disk No. :............1
Comments :...................Straight sides spec.

TEST RESULTS

	Thick./Dia In	Width In	Peak Load Lb	U.T.Stngth PSI	Yld Stngth PSI	Yld Elong. %	Brk Stngth PSI	Brk Elong. %	Modulus PSI	Energy Ft-Lb
1	0.045	0.250	895.546	799.414E+02	799.414E+02	0.430	799.414E+02	0.430	182.852E+05	0.396
2	0.046	0.249	652.097	569.776E+02	200.207E+02	4.567	569.776E+02	0.456	142.739E+05	1.648
3	0.046	0.249	791.588	691.936E+02	691.936E+02	0.302	662.257E+02	0.369	227.610E+05	0.555
4	0.045	0.250	857.465	761.110E+02	761.110E+02	0.426	761.110E+02	0.426	191.9[illegible]E+05	0.364
5	0.047	0.249	935.925	800.793E+02	800.793E+02	0.544	800.793E+02	0.544	158.040E+05	0.600
6	0.045	0.250	835.529	742.530E+02	742.530E+02	0.388	742.530E+02	0.388	193.494E+05	0.146

STATISTICS

	Thick./Dia In	Width In	Peak Load Lb	U.T.Stngth PSI	Yld Stngth PSI	Yld Elong. %	Brk Stngth PSI	Brk Elong. %	Modulus PSI	Energy Ft-Lb
Mean	0.046	0.249	828.025	727.593E+02	665.938E+02	1.110	722.647E+02	0.436	182.774E+05	0.618
Min	0.045	0.249	652.097	569.776E+02	200.207E+02	0.302	569.776E+02	0.369	142.739E+05	0.146
Max	0.047	0.250	935.925	800.793E+02	800.793E+02	4.567	800.793E+02	0.544	227.610E+05	1.648
St.Dev	0.001	0.000	99.401	872.246E+01	231.736E+02	1.696	904.337E+01	0.062	297.430E+04	0.529
% C.V.	1.689	0.173	12.005	11.988	34.795	152.825	12.514	14.121	16.273	85.642

TEST CONDITIONS

Crosshead Speed :.............	0.1	In/Min
Load Cell Capacity :..........	5000	Lb
Threshold :..................	5	% Of FSL
Break Criterion :.............	95	%
Extensometer Used :...........	1	1:Y,0:N
Gage Length :.................	1.00	In
Action @ End Of Test :........	1	1:St,0:Rtn
Crosshead Direction :.........	1	1:Up,0:Dn
Yield(Zero,Offset) :..........	0.0	0:Z,1:Off
Offset At Yield :.............	0.2	%

TABLE 4. P55 GR/AL METAL MATRIX COMPOSITES, TESTED 77K

ADVANCED MATLS. LAB

Concord, MA

Tensile Test

Batch Number: Al COMPOS.77K
Date: 04-05-87 Number of Specimens : 2

Operator I.D. :............... TA
Storage Disk No. :............ 1
Comments :.................... A16061+ C P55 #G5123

TEST RESULTS

	Thick./Dia In	Width In	Peak Load Lb	U.T.Stngth PSI	Yld Stngth PSI	Yld Elong. %	Brk Stngth PSI	Brk Elong. %	Modulus PSI	Energy Ft-Lb
1	0.046	0.250	903.135	783.502E+02	658.579E+02	0.428	783.502E+02	0.314	205.402E+05	0.197
2	0.045	0.188	786.936	933.746E+02	709.204E+02	0.426	933.746E+02	0.348	285.933E+05	0.164

STATISTICS

	Thick./Dia In	Width In	Peak Load Lb	U.T.Stngth PSI	Yld Stngth PSI	Yld Elong. %	Brk Stngth PSI	Brk Elong. %	Modulus PSI	Energy Ft-Lb
Mean	0.046	0.219	845.035	858.624E+02	683.892E+02	0.427	858.624E+02	0.331	245.668E+05	0.181
Min	0.045	0.188	786.936	783.502E+02	658.579E+02	0.426	783.502E+02	0.314	205.402E+05	0.164
Max	0.046	0.250	903.135	933.746E+02	709.204E+02	0.428	933.746E+02	0.348	285.933E+05	0.197
St.Dev	0.000	0.044	82.165	106.238E+02	357.972E+01	0.001	106.238E+02	0.024	569.436E+04	0.023
% C.V.	2.018	19.990	9.723	12.373	5.234	0.267	12.373	7.349	23.179	12.871

TEST CONDITIONS

Crosshead Speed :............. 0.1 In/Min
Load Cell Capacity :.......... 5000 Lb
Threshold :................... 5 % Of FSL
Break Criterion :............. 95 %
Extensometer Used :........... 1 1:Y,0:N
Gage Length :................. 1.00 In
Action @ End Of Test :........ 1 1:St,0:Rtn
Crosshead Direction :......... 1 1:Up,0:Dn
Yield(Zero,Offset) :.......... 1.0 1:Z,2:Off
Offset At Yield :............. 0.2 %

Since the number of tests were small, no conclusion is drawn as to the elastic modulus or tensile strength, although both appear higher than the room temperature tests.

Dog-Boned Tensile Specimens With 1/4-Inch Radius Tested at 293K

Figure 8 shows the dog-boned specimens that were tested at 293K. These specimens are listed in Table 5 as tests 3, 4, and 6. The average elastic modulus was 22.8 million psi, similar to that calculated theoretically. The ultimate tensile strength averaged 80.5 ksi, which is slightly lower than the 1-inch-radius dog-boned specimens. However, there was much data scatter. Clearly, specimen number 6 which broke in the gauge length had the highest ultimate tensile strength of 89.2 ksi.

TABLE 5. P55 GR/AL DOG BONES 1/4-INCH RADIUS, TESTED 293K

ADVANCED MATLS. LAB

Concord, MA

Tensile Test

Batch Number: Al COMPOS.293K
Date: 04-03-87 Number of Specimens : 6

Operator I.D. :............... TA
Storage Disk No. :............ 1
Comments :.................... Al6061+ C P55 #G5123

TEST RESULTS

	Thick./Dia In	Width In	Peak Load Lb	U.T.Stngth PSI	Yld Stngth PSI	Yld Elong. %	Brk Stngth PSI	Brk Elong. %	Modulus PSI	Energy Ft-Lb
1	0.047	0.250	106.628E+01	930.436E+02	794.593E+02	0.295	930.436E+02	0.400	273.702E+05	0.486
2	0.047	0.249	866.434	740.352E+02	532.938E+02	0.273	740.352E+02	0.427	196.975E+05	0.228
3	0.047	0.188	637.857	724.970E+02	247.149E+02	4.150	721.905E+02	0.432	231.368E+05	1.463
4	0.046	0.187	490.752	564.384E+02	519.172E+02	0.234	564.384E+02	0.255	223.966E+05	0.085
5	0.045	0.250	895.548	799.414E+02	182.902E+02	0.082	799.414E+02	0.407	230.582E+05	0.396
6	0.046	0.160	652.097	891.818E+02	313.366E+02	4.564	891.818E+02	0.453	229.841E+05	1.648

STATISTICS

	Thick./Dia In	Width In	Peak Load Lb	U.T.Stngth PSI	Yld Stngth PSI	Yld Elong. %	Brk Stngth PSI	Brk Elong. %	Modulus PSI	Energy Ft-Lb
Mean	0.046	0.214	771.495	775.229E+02	431.687E+02	1.600	774.718E+02	0.396	231.072E+05	0.718
Min	0.045	0.160	490.752	564.384E+02	182.902E+02	0.082	564.384E+02	0.255	196.975E+05	0.085
Max	0.047	0.250	108.628E+01	930.436E+02	794.593E+02	4.564	930.436E+02	0.453	273.702E+05	1.648
St.Dev	0.000	0.040	216.530	131.503E+02	227.840E+02	2.141	131.743E+02	0.071	246.263E+04	0.666
% C.V.	1.734	18.787	28.066	16.963	52.779	133.851	17.005	18.048	10.657	92.776

TEST CONDITIONS

Crosshead Speed :............. 0.1 In/Min
Load Cell Capacity :.......... 5000 Lb
Threshold :................... 5 % Of FSL
Break Criterion :............. 95 %
Extensometer Used :........... 1 1:Y,0:N
Gage Length :................. 1.00 In
Action @ End Of Test :........ 1 1:St,0:Rtn
Crosshead Direction :......... 1 1:Up,0:Dn
Yield(Zero,Offset) :.......... 1.0 1:Z,2:Off
Offset At Yield :............. 0.2 %

SECTION 4

SUMMARY

The volume fraction of the P55 gr/Al 6061- T6 metal matrix composite was determined to be 40 percent graphite fiber in the aluminum matrix. This was determined by analyzing micrographs of this material that was cross sectioned.

The density of the graphite fibers was determined to be 1.96 grams/cc., which was calculated from the measured density of the composite and the volume fraction of graphite fibers. This is lower than graphite single crystals that has a density of 2.25 grams/cc., Reference 5.

The modulus of elasticity of the MMC was theoretically calculated to be 28 million psi in the low stress region where the aluminum is elastic, and 22 million psi at the high stress region where the aluminum deforms plastically.

For specimens that are bent, the modulus of elasticity that is measured is less than that of a straight specimen. This is due to the straightening of the bent specimen upon loading in tension. The contribution to the lowering of the modulus of elasticity for bent specimens is shown in Figure 3.

The shape of tensile specimens influences the tensile strength as measured for the MMC. Dog-boned specimens that conform to ASTM Standard D3552-77 result in the highest tensile strengths as measured. However, straight-sided specimens result in only a fraction of a percent lower stress than the dog-boned specimens. Tabs on either end of the specimen tend to lower the tensile strength as measured if the tabs are wider than the specimen. This will cause stress concentrations that will cause fracture at a lower nominal stress. For dog-boned specimens with a radius of curvature of 1/4 inch, stress concentrations created will lower the measured tensile strength compared to specimens with a 1-inch radius of curvature.

SECTION 5

CONCLUSIONS

The following conclusions are made:

1. Volume fraction of graphite fibers of MMCs can be made by using quantitative metallography.

2. Density of graphite fibers can be obtained by weighing theMMC of measured dimensions, and using the volume fraction of fibers determined from 1 above for calculations.

3. The modulus of elasticity of the MMC can be calculated by knowing the pitch of the fibers, the modulus of elasticity of the metal matrix, and the volume fraction of the fibers.

4. The measured modulus of elasticity is reduced when testing bent specimens according to Figure 3.

5. Dog-boned tensile specimens that conform to ASTM Standard D3552-77 and straight-sided specimens give ultimate tensile strength values close to that of the intrinsic material. However, the tabs should be soft aluminum with a taper and the sides of the tabs should be the same as the specimen width where the end of the taper contacts the specimen.

SECTION 6

RECOMMENDATIONS

The following recommendations are made as a result of this work.

1. The fiber fraction and density should be determined using measuring techniques including quantitative metallography.

2. Great care should be made not to bend specimens during manufacture in order to obtain correct elastic modulus determinations.

3. Straight-sided specimens should be used due to the simplicity of manufacture. Results are close to those obtained with specimens made according to ASTM Standard D3552-77.

4. Tabs should be made of soft aluminum with a taper of about 10 degrees pointing toward the gauge length. The width of the tabs should be the same as that of the specimen. The tabs should be epoxied onto the specimen.

REFERENCES

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3. American Society for Metals Handbook, Desk Edition, (Metals Park, Ohio, ASM International 1985), pp. 6.37-6.43.

4. Baumeister, T., Ed., Mark's Standard Handbook for Mechanical Engineers, 8th Ed., (New York: McGraw Hill Book Co., Inc., 1978), pp. 5-6.

5. Weast, R. C., Ed., CRC Handbook of Chemistry and Physics, 64th Ed., (Boca Raton, Florida, CRC Press, Inc., 1984), p. B-81.

APPENDIX A

Let: b = specimen width

E = true elastic modulus

E(m) = measured elastic modulus

F = tensile force

L = 1/2 gauge length

ΔL = change in L

S = stress in specimen

t = thickness of specimen

y = bending displacement of specimen under no load

Δy = change in (y) due to force F.

R = radius of curvature of specimen

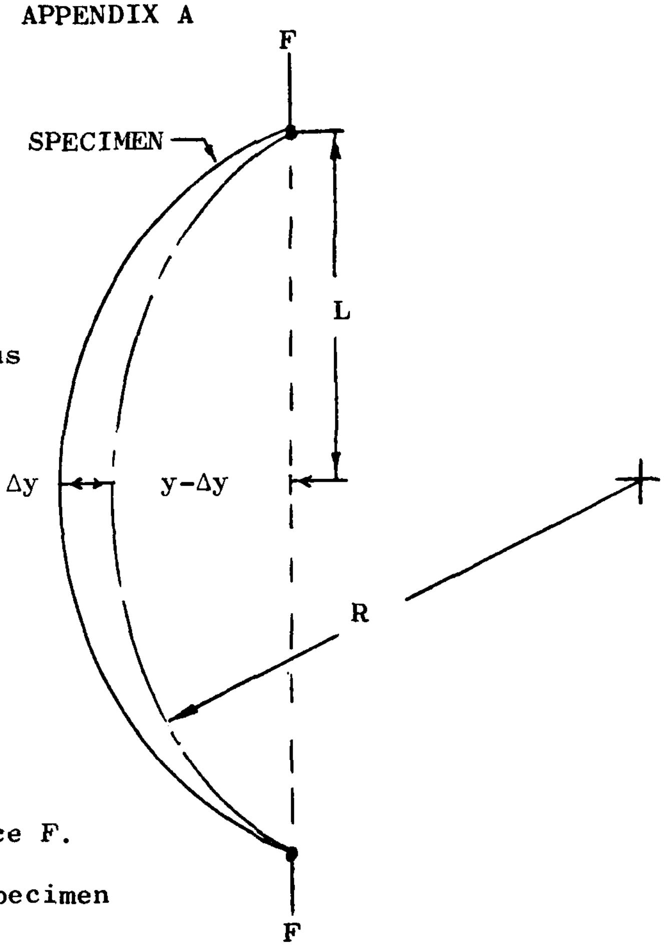

FIGURE A-1. GEOMETRY OF BENT SPECIMEN

$$\Delta y = \frac{4F(y - \Delta y)L^2}{b\ E\ t^3} \tag{8}$$

$$\Delta y = 1 - \left[\frac{1}{1 + \frac{4\ L^2}{E\ t^2}\ S}\right] y \tag{9}$$

$$R^2 = L^2 + \left[R - (y - \Delta y) \right]^2 \tag{10}$$

since $y - \Delta y \ll L$, then equation (10) reduces to:

$$y - \Delta y = \frac{L^2}{2R} \tag{11}$$

Let: ΔL_o = Change in length L to straighten specimen completely from displacement (y).

Let: ΔL_1 = change in length L to straighten specimen completely from displacement $(y - \Delta y)$

$$\Delta L_o = 2 \quad R\left[\sin^{-1}\left(\frac{L}{R}\right) - L\right]$$

by Taylor series expansion and neglecting high order terms

$$\Delta L_o = \frac{L^3}{3R^2}$$

coml .ning with equation (11), where $\Delta y = 0$ in this case,

$$\Delta L_o = \frac{4}{3}\frac{y^2}{L} \qquad (12)$$

similarly

$$\Delta L_1 = \frac{4}{3\,L}(y - \Delta y)^2 \qquad (13)$$

$$\Delta L = \Delta L_o - \Delta L_1$$

substituting equations (12) and (13)

$$\Delta L = \frac{4}{3L}\left[2y\Delta y - (\Delta y)^2\right] \qquad (14)$$

Let: ε = strain

$$\varepsilon = \frac{\Delta L}{L} + \frac{S}{E} \qquad (15)$$

combining equations (14) with (15)

$$\varepsilon = \frac{4}{3L^2}\left[2y\Delta y - (\Delta y)^2\right] + \frac{S}{E} \qquad (16)$$

combining equations (16) and (9)

$$\varepsilon = \frac{4\,y^2}{L^2}\left[1 - \frac{1}{1 - \frac{4L^2}{Et^2}}\right] + \frac{S}{E} \qquad (17)$$

differentiating equation (17) with respect to stress (S)

$$\frac{d\varepsilon}{dS} = \frac{1}{E}\left[1 + \frac{32y^2}{t^2\left(1 + \frac{4SL^2}{Et^2}\right)^3}\right] \tag{18}$$

since $E(m) = \frac{dS}{d\varepsilon}$

$$E(m)/E = 1 - \frac{32y^2}{32\ y^2 + t^2\left[1 + 4L^2S/(Et^2)^3\right]} \tag{7}$$

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